Thermal analysis of joining thermoplastic composites using microwaves

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Abstract: Industrial microwave technology for processing polymers and polymer-based composites is currently in a state of considerable flux. Ku et al. (1997a; 1997b; 1999a) used the equipment shown in Figure 1 to join random glass or carbon fibres reinforced thermoplastic composites. The material used for the research is 33% by weight random glass fibre reinforced low-density polyethylene [LDPE/GF (33%)] using Araldite as primer. The heat absorbed and heat flow in the sample materials are studied. The temperatures at different points of the samples are also measured using infrared thermometer. The effect of power input and cycle time on the temperature distribution in the test piece is detailed together with the underlying principles of sample material interactions with electromagnetic field.

Keywords: relative complex relative permittivity, loss tangent, 33% by weight random glass fibre-reinforced low-density polyethylene, curing, lap shear bond strength and microwaves.

Introduction

The general mechanisms that govern the energy dissipation process and the microwave/material interaction include dipole friction, current loss and ion jump relaxation (Metaxas and Meredith, 1983; Siores, 1994). The growth in using thermoplastic composites in structural materials remains very strong and welding technology development fuels that growth (Schwartz, 1992). The advantages of using thermoplastic composites over the frequently used thermosetting composites include their capability to be formed into complex shapes at lower costs and high productivity rates. Most thermoplastic composites are joined
by fusion bonding and the processes employed consist of resistance welding, ultrasonic bonding, vibrational bonding, high frequency welding, traditional infrared heated air, hot plate, hot melt and room-cure adhesives (Varadan and Varanda, 1991; Partridge, 1989). The merits of employing microwaves in joining thermoplastics composites include having a clean and reliable interface at the joints and fast joining time with minimum destruction of the properties of the bulk materials (Varanda and Varanda, 1991). Limitations encountered in other processes are also avoided.

Referring to Figure 1, the microwaves generated from the magnetron are guided through WR340 waveguide to the test pieces. Avoiding radiation leakage is of primary concern and the joining process is enclosed within a microwave oven cavity so that microwave will not radiate to the surrounding environment.

**Microwave and peripheral facilities**

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 plunger was designed and manufactured to have a sliding fit contact with the
waveguide. The interaction between the incident and the reflected waves sets up a standing wave and it is desirable that the maximum electric field occurs at the seam of the lapped test pieces (Glazier and Lamont, 1958). This was achieved by adjusting the moveable piston so that its top face is an odd multiple of $\lambda_g/4$ from the centre of the slit; where $\lambda_g$ is the wavelength within the waveguide.

**Materials microwaves interaction considerations**

High energy rate joining of thermoplastic composites using microwave was studied because it was believed that the microwave/materials interactions of some of thermoplastic composites with and without fillers will favour the process. The material properties of greatest importance in microwave processing of a dielectric are the complex relative permittivity $\varepsilon = \varepsilon' - j\varepsilon''$, and the loss tangent, $\tan \delta = \varepsilon''/\varepsilon'$. The real part of the permittivity, $\varepsilon'$, sometimes called the dielectric constant, mostly determine 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. For optimum microwave energy coupling, a moderate value of $\varepsilon'$, to enable adequate penetration, should be combined with high values of $\varepsilon''$ and $\tan \delta$, to convert microwave energy into thermal energy (NRC, 1994). 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. For a material having a polar molecule eg water, the real and imaginary parts of the permittivity vary with frequency as shown in Figure 2. Because of the skin effect, it may not be possible to work at the relaxation frequency. The 2.45 GHz frequency was chosen because it seems that it has been the most popular choice for property measurement and the magnetrons for that frequency are most readily available (Metaxas and Meredith, 1983).
Random glass fibre reinforced (33%) LDPE was selected because there were successful cases of welding the composite with high density polyethylene (HDPE) as matrix using microwave energy and it was believed that LDPE will couple better to microwaves as its crystallinity is lower than the HPDE (Wu and Benatar, 1992; NRC, 1994; Ku et al., 1997a; 1997b). The composite is not readily available in the market and it was specially manufactured in Plastic and Rubber Technical Education Centre (PARTEC) in Brisbane, Australia. The length of the reinforcing fibre was 6 mm or less and the test pieces were injection-moulded to shape. However, typical lengths of fibres used in reinforced injection moulding materials were 0.8 to 25 mm (Strong, 1989).

**Test piece microwave interaction results**

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 millimeteres 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 3. This is to fix the relative position between the two test pieces and to apply pressure onto the lap joint. The pressure on the lap joint was estimated to be 4 N/cm² and it was critical as the bond strengths of the test pieces cured by leaving them in ambient conditions for one hours with and without the rubber band pressure were 153 N/cm² and 84 N/cm² respectively. 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 4. The dielectric band was made to push the two pieces when the interface was melted by microwave energy and joined them together. 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 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 5) were measured using infrared thermometer. $E$ is the mid point of the lapped test pieces with $E_{L1}$ and $E_{R1}$ are at 10 mm from left and right of $E$ respectively. Similarly, $E_{L2}$ and $E_{R2}$ are at 20 mm from left and right from $E$ respectively and so on for $E_{L3}$ and $E_{R3}$ and $E_{L4}$ and $E_{R4}$ respectively. Referring to Figure 5, 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 lapped area contained the Araldite, which absorbed microwave energy and converted it into heat. Figure 6 shows the temperature distribution of samples 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 longer the duration of exposure to microwave energy, the higher the temperatures of the points as depicted in Figure 6. 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 the angle $E_{L1}EE_{R1}$; at shorter duration of microwave irradiation, the angle could be 180°, ie, there were not much temperature difference between $E$ and $E_{L1}$, and $E$ and
respectively (see the 20 second-exposure in Figure 6) and the temperature was not 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 not much higher than the ambient temperature. The rise in temperature might have been due to the heat conducted from the lapped area where the Araldite had absorbed more microwave energy. It can also be noted that the temperatures of the points to the left of the lapped area were more or less the same to those on the right because the test pieces were inserted into the rectangular waveguide through the slit symmetrically and the electric fields inside the waveguide were also symmetrical.

Figure 7 shows the temperature distribution of samples 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 $32 \, ^{\circ}C$, $34 \, ^{\circ}C$ and $31.5 \, ^{\circ}C$ respectively. The ambient temperature was $21 \, ^{\circ}C$. The oven cavity temperature after bonding for an exposure time of 240 seconds was $27 \, ^{\circ}C$. The mid-point of the sample, point $E$, was hottest and it was $13 \, ^{\circ}C$ higher than the room temperature. The longer the duration of exposure to microwave energy, the higher the temperature of the points as depicted in Figure 7. 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 the angle $E_{L1}EE_{R1}$; at shorter duration of microwave irradiation, the angle would be obtuse, ie, there were no significance difference in temperature between $E$ and $E_{L1}$, and $E$ and $E_{R1}$ respectively but the temperatures were much higher than the ambient temperature. The temperature distribution along the points considered (see Figure 7) is similar to that of the 800 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 800 W microwave irradiation mentioned above.

**Heat flow and temperature gradient**

Figure 8 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 Wm\(^{-1}\)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, K;

\(A\) = cross-sectional area in m\(^2\);
\( L \) = length of sample in m.

Referring to Figure 5 and consider the case when the test pieces were exposed to microwave irradiation for 70 seconds at a power level of 800 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\(^2\) from points, E to \( E_{R4} \), to 20 x 3 mm\(^2\) from points \( E_{R4} \) 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 LDPE/GF (33\%) was simulated from those of its constituent materials and was found to be 0.8692 Wm\(^{-1}\)K\(^{-1}\) (Callister, 2003).

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

\[
\frac{Q}{t} = kA \frac{\theta_1 - \theta_2}{L} = 0.8692 \times 41.82 \times 10^{-6} \times \frac{33.5 - 27}{66 \times 10^{-3}} = 3.58 \times 10^{-3} \text{ W}
\]

or energy flow = \( Q = 3.58 \times 10^{-3} \times 70 = 0.251 \text{ J} \)

Similarly, the heat flow rate, \( \frac{Q}{t} \) from points, E to \( E_{R3} \) and E to \( E_{R1} \) are 4.35 x 10\(^{-3}\) W and 5.22 x 10\(^{-3}\) W respectively. Furthermore, energy flow, \( Q \) from points, E to \( E_{R3} \) and E to \( E_{R1} \) are 0.304 J and 0.365 J respectively. The values for \( \frac{Q}{t} \) and \( Q \) are very small and are due to the small value of thermal conductivity of LDPE/GF (33\%).

Now consider the heat absorbed by different sections of the test pieces. With reference to Figure 8, Equation 1 and Equation 2 are not linear and they represent the change of
temperature with positions along the test pieces to the left of the centre point, E and to the right of it respectively. The slope of polynomials at a particular point along the sample represents the temperature gradient on that location. They can be obtained by Lagrange quadratic interpolation (Kreyszig, 1999). As manual method is tedious, MATLAB 6 software package is used to obtain the two equations. The temperature values recorded along the length of the test pieces with microwave exposure time of 70 seconds at 800 W were used to find Equations 1 and 2 (Figure 8). A loop is used to construct the coefficients of polynomial product in the numerator of each component polynomial and also the product in the denominator. CONV function (convolution of two vectors) in MATLAB is used to obtain the coefficients of a polynomial product.

To do this in MATLAB (for Equation 1) first define the variables l and T, using MATLAB’s automatic linear interpolation. The Lagrange polynomial will be called P and it will be constructed piecemeal, beginning with $P=0$. Then for each data point the coefficients for the corresponding $L_k$ (base) polynomial will be constructed as follow:

```matlab
l=[-66 -40 -30 -20 -10 0];
T=[27 27.5 28.5 30.5 31.5 33.5];
P=0
for k=1:6
    u = l(l~=l(k));       % pick out the values of $l$ other than $l_k$
    p = [1, -u(1)];       % first factor in the polynomial product
    q = l(k) -u(1);      % first factor in the denominator
    for j=2:5
        p = conv (p, [1, -u(j)]); % polynomial multiply by each successive factor
    end
    P = conv (P, p);
end
```

```matlab
l=[-66 -40 -30 -20 -10 0];
T=[27 27.5 28.5 30.5 31.5 33.5];
P=0
for k=1:6
    u = l(l~=l(k));       % pick out the values of $l$ other than $l_k$
    p = [1, -u(1)];       % first factor in the polynomial product
    q = l(k) -u(1);      % first factor in the denominator
    for j=2:5
        p = conv (p, [1, -u(j)]); % polynomial multiply by each successive factor
    end
    P = conv (P, p);
end
```
\[
q = q^* (l(k) - u(j)); \quad \text{% multiply denominator by each successive factor}
\]
\[
r = p/q; \quad \text{% coefficients of the base component polynomial}
\]
end
\[
P = P + T(k) * r; \quad \text{% The Lagrange polynomial}
\]
end
\[
\text{fprintf(''}\%1.8f', \text{P})
\]

In fact the coefficients of this polynomial (Equation 1) are 0.00000052, 0.00005256, 0.0034, 0.063876, 0.50281 and 33.5 so that the polynomial values will be computed from
\[
T(l) = 0.00000052x^5 + 0.00007215x^4 + 0.0034x^3 + 0.063876x^2 + 0.56627x + 33.5
\]

Similarly, Equation 2 is
\[
T(l) = -0.00000036x^5 + 0.00005256x^4 - 0.00259x^3 + 0.05128x^2 - 0.50281x + 33.5
\]

From these two equations, the temperature of a particular location along the samples can be easily computed. Equations 1 and 2 for other duration of exposure to microwaves at powerlevels of 400 W and 800 W can be similarly obtained. In addition, by substituting the values of maximum temperature at positions E (see Figure 5) for each duration of exposure to \textit{CONV} function in MATLAB, a polynomial, Equation 3 = 0.00000841x^4 - 0.0014143x^3 + 0.0823x^2 - 1.8354x + 41.75 for finding the temperature at location E in the test pieces and at a particular duration of exposure can be obtained. By using this polynomial, Equation 3 and Equations 1 and 2 for different duration of exposure, the temperatures along the samples at a particular time of exposure can be estimated.

The specific heat capacity of LDPE/GF (33\%) was simulated from those of its constituents and was found to be 1510 Jkg\(^{-1}\)K\(^{-1}\) (Callister, 2003). By referring to Figure 5, 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 $E_{R1}$ of LDPE/GF (33%), the temperature of $E$ and $E_{R1}$ after exposing to microwaves of 800 W for 70 seconds were 33.5 °C and 31.5 °C respectively. Their average temperature was \( \frac{33.5°C + 31.5°C}{2} = 32.5 °C \). The volume of the section = 10 mm x 10 mm x 3 mm x 2 (lapped area) = 600 mm\(^3\). 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 7.42 g. Since the total volume of the test pieces was 6200 mm\(^3\) or 6.2 cm\(^3\), the density of LDPE/GF (33%) = \( \frac{mass}{volume} = \frac{7.42 g}{6.2 cm^3} = 1.2 g/ cm^3 \). The mass of section $E$ and $E_{R1}$ = volume x density = 0.6 cm\(^3\) x 1.2 g/ cm\(^3\) = 0.72 g. The microwave power absorbed =

\[
= 0.72 g \times 1510 J/kg^{-1}K^{-1} \times [(32.5 + 273) K - (21 + 273) K] = 12.504 J
\]

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. Only very small amount, probably, 0.2 % came from heat flow from the centre of the sample, $E$. Despite the low loss of the composite
material, LDPE/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.

**Lap shear bond strengths**

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). The results are summarised in Figure 9. Referring to Figure 9 and at a power level of 800 W, the cluster of bond strengths, at microwave exposure times ranging from 25 to 40 seconds, were best represented by the line 800PE1, their average value; while those resulting from microwave energy exposure in a range of 45 to 65 seconds were averaged as line. In both cases, the results obtained were similar with the work of another researcher in Australia using high-density polyethylene (Siores et al., 1997). A step function was formed; at shorter exposure times, the average bond strength was only 97% of that cured in ambient conditions and it could be argued that no diffusion of parent material to the primer had taken place. When longer exposure times were used, the average bond strength became 41% higher. The processing times were also merely 0.96% and 1.6 % respectively of the conventional ones. At a power level of 400 W, the cluster of bond strengths, obtained by exposing to microwaves from 135 to 240 seconds, were best represented by the line 400PE1, their average value, was 18 % higher than that cured in ambient conditions and the processing time was only 3.89 % of its rival (Ku et al., 2002a; 2002b). The average lap shear strength of test pieces cured conventionally was relatively low, 156 N/cm², as indicated by the manufacturer’s instructions of the adhesive (Selleys, undated).

**Relationship between temperature distribution and lap shear bond strength**
Figure 10 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, i.e., 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 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, i.e., 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$^2$). When compared with the ambient cured samples, the increase in lap shear strength was 45% (Ku et al., 1997b: 2002a; 2002c). 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 11 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$^2$). It can be argued that values of the lap shear strength were not high, but the rise in temperatures in the test pieces were significant enough to cure the Araldite rapidly (Ku et al., 1997b: 2002a; 2002c). Exposure times of over 240 seconds will deform the samples.
Conclusions

The potential benefits of the technology will speed up the replacement of thermosetting resins by advanced thermoplastic composites in the structural parts of aeronautical, military and recreational industries. The constituent elements of the composite, LDPE with loss tangent at 2.45 GHz = 3.6 \times 10^{-4}, and GF with loss tangent = 5.3 \times 10^{-5} are low loss material and it is therefore expected that the composite itself, LDPE/GF (33%) with loss tangent at 2.45 GHz = 2.6 \times 10^{-4} is a low loss material as well (Metaxas and Meredith, 1983; Ku et al., 1999b). The Araldite with loss tangent at 2.45 GHz = 0.244, therefore plays a vital role in absorbing microwave energy and converted it into heat and cures itself rapidly (Ku et al., 2001).

Power level of microwaves used and the duration of exposure of the samples to microwave irradiation also play important role in the heating and curing of the Araldite. With reference to Figure 6, it can be noticed that if the power level of microwaves used is relatively low, say, 400W, the exposure duration must be long, otherwise no bonding will take place. In this case, no proper joint could be obtained if the exposure time was less than 135 seconds (Ku et al., 1997b). On the other hand, if the power level used is relatively high, say, 800 W, the exposure duration can be shorter, but it must still be up to certain value, otherwise, bonding will not occur properly. This is clearly illustrated in Figure 9. When the exposure duration was less than 40 seconds, the Araldite could not be fully cured even if a rise in temperature in the sample was recorded. The resulting bond strength was weak, even weaker than test pieces with Araldite cured under ambient conditions. From the above observation, it can be argued that the bond in the lapped area is going to form properly only if the rise in temperature is significant enough to cause the complete curing of the Araldite in a short time. By observing the relationship of lap shear strengths, temperature at centre points and duration of exposure
to microwave irradiation in Figures 10 and 11, one can deduce that when the temperature on
the centre of the sample is over 30 °C, the Araldite will have been cured properly and quickly,
and the resulting bond strength will be good. However, it must be noted that too high a
temperature is not welcomed because the primer will be over-cured and the lap shear strength
will be weakened. In addition, the dielectric band used to apply pressure on the lapped area
of the test pieces will also deform them because at higher temperatures the samples will be
very soft and can be deformed with ease (Ku et al., 1997a: 1997b).

In microwave processing of materials, most of the heat absorbed by the samples is due to the
absorption of microwave irradiation and then conversion of the microwaves into heat by the
samples. The heating effect due to heat flow from the hottest part of the samples to the cooler
parts is not significant, particularly of the thermal conductivity of the material is low like
LDPE/GF (33%).

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Figure 1. Microwave Facilities Configuration

Figure 2: Dielectric Relaxation of Typical Polar Dielectric
Figure 3: Test Pieces tightened by a Dielectric Band

Figure 4: Test Pieces in Position
Figure 5: Locations at which temperature measurements (in the sample) are taken

Figure 6: Temperature at different locations in samples with different exposure duration to 800 W microwave irradiation

Temperatures at different locations at a power level of 800W microwave irradiation, LDPE/GF (33%)
Temperatures at different locations at a power level of 400W microwave irradiation, LDPE/GF (33%)

Figure 7: Temperature at different locations in samples with different exposure duration to 400 W microwave irradiation
Figure 8: Heat flow and temperature gradient of test pieces exposed to a power level of 800 W and a duration of 70 seconds.
Figure 9: Lap Shear Strength of LDPE/GF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide using Rapid Araldite

Figure 10: Lap shear bond strength and temperature against time of exposure to microwaves of 800W in the samples of LDPE/GF (33%)
Figure 11: Lap shear bond strength and temperature against time of exposure to microwaves of 400W in the samples of LDPE/GF (33%)

Table 1: Volume and Average Temperature of Different Sections of Test Pieces

<table>
<thead>
<tr>
<th>Sections</th>
<th>Volume (mm³)</th>
<th>Average temperature (°C)</th>
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<tbody>
<tr>
<td>Rest on left</td>
<td>1600</td>
<td>27</td>
</tr>
<tr>
<td>E₁₄ and E₁₃</td>
<td>300</td>
<td>27.75</td>
</tr>
<tr>
<td>E₁₃ and E₁₂</td>
<td>300</td>
<td>29.5</td>
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<td>31</td>
</tr>
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<td>600</td>
<td>32.5</td>
</tr>
<tr>
<td>E and E₁₁</td>
<td>600</td>
<td>32.5</td>
</tr>
<tr>
<td>E₁₁ and E₁</td>
<td>300</td>
<td>31</td>
</tr>
<tr>
<td>E₁₂ and E₁</td>
<td>300</td>
<td>29.5</td>
</tr>
<tr>
<td>E₁₃ and E₁</td>
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<td>28</td>
</tr>
<tr>
<td>Rest on right</td>
<td>1600</td>
<td>27</td>
</tr>
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</table>

Table 2: Mass and Energy of Different Sections of Test Pieces

<table>
<thead>
<tr>
<th>Sections</th>
<th>Mass (g)</th>
<th>Energy absorbed (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest on left</td>
<td>1.92</td>
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