Thermal analysis of joining Nylon 66 composites using microwave irradiations

H S Ku*, B Widjaya+, K F Lee* and CW Li*

*Faculty of Engineering and Surveying, University of Southern Queensland, West Street, Toowoomba, 4350, Australia.

+P T Indodaya Cipta Lestari, Kapuk Raya 21, Jalan Nusa Indah No. 21, Jakarta 11720, Indonesia.

E-mail: ku@usq.edu.au

Abstract: Industrial microwave technology for processing polymers and polymer-based composites is currently in a state of considerable flux. Ku et al. used the equipment used in his previous study to join random glass or carbon fibres reinforced thermoplastic composites (Ku et al., 1997a; 1997b; 1999, 2002b). The material used for the research is 33% by weight random glass fibre reinforced Nylon 66 [Nylon 66/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 are 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 nylon 66, 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, E, 1994). The growth in using thermoplastic composites in structural materials remains very strong and welding technology development fuels that growth (Schwartz, M M, 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 Varadan, 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 (Varadan and Varadan, 1991). Limitations encountered in other processes are also avoided.

**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.

As in the previous study, the incident waves are generated by the magnetron (Ku et al., 1997a). 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 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 example a material having a polar molecule like water, the real and imaginary parts of the permittivity vary with frequency as shown in Figure 1. 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%) nylon 66 was selected because it was readily available in Australian market and its loss tangent is estimated to be high and will absorb microwave energy readily.

**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 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 (Ku et al., 2002b). 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/cm$^2$ 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 376 N/cm$^2$ and 83 N/cm$^2$ 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 2. 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 240W and 400W 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 (Selleys, undated). This is in line with the work of other researchers in the United States (Paulauskas, et al., 1996).
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 3) 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 3, 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, \( E_{L4}, E_{L3}, \ldots E, \ldots E_{R3} \) 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 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 16 °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 4. 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 \( E_{R1} \) respectively (see the 15 second-exposure in Figure 4) 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 5 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 longer the duration of exposure to microwave energy, the higher the temperature of the points as depicted in Figure 5. The temperature distribution along the points considered (see Figure 5) is similar to that of the 400 W microwave power exposure in Figure 4. 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 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.

**Heat flow and temperature gradient**

Figure 6 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 \( \text{W m}^{-1} \text{K}^{-1} \);

\( Q \) = 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, K;

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

\( L \) = length of sample in m.

Referring to Figure 3 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\(^2\) 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 Nylon 66/GF (33\%) was simulated from those of its constituents and was found to be 0.721 Wm\(^{-1}\)K\(^{-1}\) (Callister, 2003).

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

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

or energy flow = \( Q = 4.960 \times 10^{-3} \times 30 = 0.149 \text{ J} \)

Similarly, the heat flow rate, \( \frac{Q}{t} \) from points, \( E \) to \( E_{R3} \) and \( E \) to \( E_{R1} \) are 3.780 x 10\(^{-3}\) W and 4.530 x 10\(^{-3}\) W respectively. Furthermore, energy flow, \( Q \) from points, \( E \) to \( E_{R3} \) and \( E \) to \( E_{R1} \) are 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\%).

Now consider the heat absorbed by different sections of the test pieces. With reference to Figure 6, 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 30 seconds at 400 W were used to find Equations 1 and 2 (Figure 6). 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. \textit{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 Langrange 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:

\[
l= [66 40 30 20 10 0];
\]
\[
T= [24 24.5 26.5 29.5 34 35];
\]
\[
P=0
\]

for k=1:6

\[
u = l(l\sim=l(k)); \quad \text{% pick pout the values of } S1S \text{ other than } S1_kS
\]
\[
p = [1, -u(1)]; \quad \text{% first factor in the polynomial product}
\]
\[
q = l(k) -u(1); \quad \text{% first factor in the denominator}
\]

for j=2:5

\[
p = \text{conv} (p, [1, -u(j)]); \quad \text{% polynomial multiply by each successive factor}
\]
\[
q = q* (l(k) -u(j)); \quad \text{% multiply denominator by each successive factor}
\]
\[
r = p/q; \quad \text{% coefficients of the base component polynomial}
\]
end
\[
P = P + T(k) *r; \quad \text{% The Lagrange polynomial}
\]
end
\[
\text{fprintf(``\%1.8f\'', P)}
\]
In fact the coefficients of this polynomial (Equation 1) are 0.0000037, 0.00005991, 0.00350297, 0.08620307, 0.46794142 and 35. Therefore, the polynomial is

\[ T(I) = 0.0000037x^5 + 0.00005991x^4 + 0.00350297x^3 + 0.08620307x^2 + 0.46794142x + 35 \]

Similarly, Equation 2 is

\[ T(I) = -0.00000077x^5 + 0.00012050x^4 - 0.00656123x^3 + 0.14149972x^2 - 0.67169865x + 35 \]

From these two equations, the temperature of a particular location along the samples can be easily computed. Equations 1 and 2 for others duration of exposure to microwaves at power levels of 240 W and 400 W can be similarly obtained. In addition, by substituting the values of maximum temperature at positions E (see Figure 3) for each duration of exposure to CONV function in MATLAB, a polynomial, Equation 3 = 0.0007431x^4 - 0.01117x^3 + 0.5498x^2 - 10.251x + 88.98 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 Nylon 66/GF (33%) was simulated from those of its constituents and was found to be 1394 Jkg^{-1}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. Consider the section of E and E_{R1} of Nylon 66/GF (33%), the temperature of E and E_{R1} after exposing to microwaves of 400 W for 30 seconds were 35 °C and 34 °C respectively. Their average temperature was \[ \frac{35°C + 33°C}{2} = 34°C \]. 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 10.75 g. Since the total volume of the test pieces was 6200 mm³ or 6.2 cm³, the 
density of LDPE/GF (33%) = \( \frac{\text{mass}}{\text{volume}} = \frac{10.75 \text{ g}}{6.2 \text{ cm}^3} = 1.73 \text{ g/cm}^3 \). The mass of section E and 
\( E_{R1} = \text{volume x density} = 0.6 \text{ cm}^3 \times 1.73 \text{ g/cm}^3 = 1.04 \text{ g} \). The microwave power absorbed = 
(mass) x (specific heat capacity) x (rise in temperature) 
= 1.04 g x 1394 J/kg°C x [(34 + 273) K – (24 + 273) K] = 21.746 J

The mass and energy absorbed of other sections can be similarly calculated and are shown in 
Table 1. 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). 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 overwhelming 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). Figure 7 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 9. 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 9 and at a power level of 400 W, an exposure time to microwaves of
over 35 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; 1999). 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.

Relationship between temperature distribution and lap shear bond strength
Figure 8 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$^2$ 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 and the Araldite was overcured. The lap shear strength dropped (Ku et al., 1997a; 1997b; 1999). When compared with the ambient cured samples, the increase in lap shear strength was 32 % (Ku et al., 1997b; 2002a; 2002b). 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 9 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 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; 2002a; 2002b). The primer became overcured when exposed to microwaves for more than 55 seconds.

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, Nylon66 with loss tangent at 2.45 GHz = 107 x 10^{-4}, and GF with loss tangent = 5.3 x 10^{-5} are medium and low loss materials respectively and it is therefore expected that the composite itself, Nylon 66/GF (33%) with loss tangent at 2.45 GHz = 71.9 x 10^{-4} is a low to medium loss material as well (Metaxas and Meredith, 1983). 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 9, it can be noticed that if the power level of microwaves used is relatively low, say, 240W, 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 50 seconds (Ku et al., 1997b). On the other hand, if the power level used is relatively high, say, 400 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 25 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 8 and 9, 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 Nylon 66/GF (33%).

Acknowledgement

Many thanks have to be given to my colleague, Dr. Tony Ahfock, Senior Lecturer, Faculty of Engineering and Surveying, University of Southern Queensland for his assistance in translating the abstract of the paper into French in accordance with the requirements of the Transactions, Canadian Society of Mechanical Engineers.

References


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


Selleys, (undated), Araldite five minute epoxy adhesive user instructions, p. 1, 1 Gow Street, Padstow, NSW 2211, Australia.

Figure 1: Dielectric Relaxation of Typical Polar Dielectric

Figure 2: Test Pieces in Position
Figure 3: Locations at which temperature measurements (in the sample) are taken

Figure 4: Temperature at different locations in samples with different exposure duration to 400 W microwave irradiation

Temperatures at different locations at a power level of 400W microwave irradiation, Nylon 66/GF (33%)
Temperatures at different locations at a power level of 240W microwave irradiation, Nylon/GF (33%)

Figure 5: Temperature at different locations in samples with different exposure duration to 240 W microwave irradiation
Figure 6: Heat flow and temperature gradient of test pieces exposed to a power level of 400 W and a duration of 30 seconds.
Figure 7: Lap Shear Strength of Nylon 66/GF (33%) Joined by Fixed Frequency Microwave (2.45 GHz) in a Slotted Rectangular Waveguide using Rapid Araldite

Figure 8: Lap shear bond strength and temperature against time of exposure to microwaves of 400W in the samples of Nylon 66/GF (33%)
Figure 9: Lap shear bond strength and temperature against time of exposure to microwaves of 240W in the samples of Nylon 66/GF (33%)

Table 1: Volume, Mass, Average Temperature and Energy Absorbed of Different Sections of Test Pieces of Nylon 66/GF (33%)

<table>
<thead>
<tr>
<th>Sections</th>
<th>Volume (mm³)</th>
<th>Mass (g)</th>
<th>Average temperature (°C)</th>
<th>Energy absorbed (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest on left</td>
<td>1600</td>
<td>2.77</td>
<td>24.25</td>
<td>20.272</td>
</tr>
<tr>
<td>El4 and El3</td>
<td>300</td>
<td>0.52</td>
<td>25.50</td>
<td>4.711</td>
</tr>
<tr>
<td>El3 and El2</td>
<td>300</td>
<td>0.52</td>
<td>28.00</td>
<td>6.523</td>
</tr>
<tr>
<td>El2 and El1</td>
<td>300</td>
<td>0.52</td>
<td>31.75</td>
<td>9.242</td>
</tr>
<tr>
<td>El1 and E</td>
<td>600</td>
<td>1.04</td>
<td>34.50</td>
<td>22.471</td>
</tr>
<tr>
<td>E and Er1</td>
<td>600</td>
<td>1.04</td>
<td>34.00</td>
<td>21.746</td>
</tr>
<tr>
<td>Er1 and Er2</td>
<td>300</td>
<td>0.52</td>
<td>30.50</td>
<td>8.336</td>
</tr>
<tr>
<td>Er2 and Er3</td>
<td>300</td>
<td>0.52</td>
<td>26.75</td>
<td>5.618</td>
</tr>
<tr>
<td>Er3 and Er4</td>
<td>300</td>
<td>0.52</td>
<td>25.75</td>
<td>4.893</td>
</tr>
<tr>
<td>Rest on right</td>
<td>1600</td>
<td>2.77</td>
<td>24.75</td>
<td>22.203</td>
</tr>
</tbody>
</table>