Thermal Analysis Comparison between Two Random Glass Fibre Reinforced Thermoplastic Matrix Composites Bonded by Adhesives using Microwaves: Preliminary Results

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Abstract: This paper compares the thermal analysis of two 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 polystyrene composite [PS/GF (33%)] and thirty three percent by weight random glass fibre reinforced low density polyethylene composite [LDPE/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 two 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.

1. 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, $\tan \delta = \varepsilon''/ \varepsilon'$ [1, 2]. The real part of the permittivity, ε', sometimes called the dielectric constant, mostly determines how much of the incident energy is reflected at the air-sample interface, and how much is

absorbed. The most important property in microwave processing is the loss tangent, tan δ, which predicts the ability of the material to convert the absorbed energy into heat. In this study low-density polyethylene and polystyrene are the thermoplastic matrices used. 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 cyrstallinity is lower than that of HPDE [2, 3]. In addition, polyethylene is used more than any other thermoplastic polymers. However, the composite was not readily available in the Australian market and 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 [4-6]. The composite was also manufactured by PARTEC.

2. 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. After tightening with a dielectric band, the two halves of the test pieces were positioned in the slot across the waveguide. 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^{o}C before being lap shear tested to obtain maximum bond strength [7].

3. 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 2) were measured using infrared thermometer. Referring to Figure 2, 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 3 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 ^{o}C, 33 ^{o}C and 31.5 ^{o}C respectively. The ambient temperature was 21 ^{o}C. The oven cavity temperature after bonding for 60 seconds of microwave exposure was 27 ^{o}C. The mid-point of the sample, point E, was hottest and it was 12 ^{o}C higher than the room temperature. 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. At shorter duration of microwave irradiation, the angle was obtuse but the temperature was much higher than the ambient temperature.

Figure 4 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 ^{o}C, 36 ^{o}C and 31.5 ^{o}C respectively. The ambient temperature was 21 ^{o}C. The oven cavity temperature after bonding for an exposure time of 240 seconds was 27 ^{o}C. The temperature distribution along the points considered (see Figure 4) is similar to that of the 800 W microwave power exposure in Figure 3. 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.

Figure 5 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 ^{o}C, 33.5 ^{o}C and 31.5 ^{o}C respectively. The ambient temperature was 21 ^{o}C. The oven cavity temperature after bonding for 70 seconds of microwave exposure was 27 ^{o}C. The mid-point of the sample, point E, was hottest and it was 12.5 ^{o}C higher than the room temperature.

Figure 6 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 ^{o}C, 34 ^{o}C and 31.5 ^{o}C respectively. The ambient temperature was 21 ^{o}C. The oven cavity temperature after bonding for an exposure time of 240 seconds was 27 ^{o}C.

4. Heat Flow and Temperature Gradient

Figure 7 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 dθ is the temperature difference between the two positions. The heat flow along the sample depends on [8]:

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, $\frac{Q}{t} = kA\frac{(\theta_1 - \theta_2)}{L}$ [8].

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.

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

Referring to Figure 2 and consider the case when the test pieces were exposed to microwave irradition for 60 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 PS/GF (33%) was measured to be 0.648 $Wm^{-1}K^{-1}$ [9].

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

$$\frac{Q}{t} = kA\frac{(\theta_1 - \theta_2)}{L} = 0.648 \text{ x } 41.82 \text{ x } 10^{-6} \text{ x } \frac{(33-27)}{66x10^{-3}} = 2.464 \text{ x } 10^{-3} \text{ W}$$

or energy flow = Q = 2.464 x 10^{-3} x 60 = 0.148 J.

Similarly, the heat flow rate, $\frac{Q}{t}$ from points, E to E_{R3} and E to E_{R2} are 0.585 x 10^{-3} W and 0.614 x 10^{-3} W respectively. Furthermore, energy flow, Q from points, E to E_{R3} and E to E_{R1} are 0.194 J and 0.204 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%).

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 [10]. As manual method is tedious, MATLAB 6 software package is used to obtain the two equations.

The coefficients of this polynomial (Equation 1) are 0. 00000052, 0.00007325, 0.0034, 0.056623, 0.40079 and 33. The polynomial values will then be computed. Therefore,

$T(l) = 0.00000052x^5 + 0.00007325x^4 + 0.0034x^3 + 0.056623x^2 + 0.40079x + 33$

Similarly, Equation 2 is

$T(l) = -0.00000052x^5 + 0.00007325x^4 - 0.0034x^3 + 0.056623x^2 - 0.40079x + 33$

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 power levels of 400 W and 800 W can be similarly obtained. In addition, by substituting the values of maximum temperature at positions E (see Figure 10) for each duration of exposure to *CONV* function in MATLAB, a polynomial, Equation 3 = $-0.0000087x^5 + 0.000160x^4 - 0.01115x^3 + 0.3633x^2 – 5.4x + 0.955$ for finding the temperature at location E in the test pieces and at a particular duration of exposure to microwaves can be obtained. By using 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 PS/GF (33%) was simulated from those of its constituents and was found to be 1061 $Jkg^{-1}K^{-1}$ [9]. By referring to Figure 2, 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 PS/GF (33%), the temperature of E and E_{R1} after exposing to microwaves of 800 W for 70 seconds were 33.5 ^oC and 31.5 ^oC respectively. Their average temperature was $\frac{33^oC + 31.5^oC}{2} = 32.25\,^oC$. 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 9.80 g. Since the total volume of the test pieces was 6200 mm^3 or 6.2 cm^3, the density of PS/GF (33%) = $\frac{mass}{volume} = \frac{9.80g}{6.2cm^3}$ = 1.58 g/ cm^3.

The mass of section E and E_{R1} = volume x density = 0.6 cm^3 x 1.58 g/ cm^3 = 0.95 g. The microwave power absorbed

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

= 0.95g x 1061 $Jkg^{-1}K^{-1}$ x [(32.25 +273) K – (21 +273) K] = 11.339 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 was 86 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. 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, PS/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.

6. Heat flow in LDPE/GF (33%) test pieces

Referring to Figure 2, 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 is the same as above and equals 41.82 mm^2. The thermal conductivity of LDPE/GF (33%) was simulated from its constituents and was found to be 0.8692 $Wm^{-1}K^{-1}$ [9]

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

$$\frac{Q}{t} = kA\frac{(\theta_1 - \theta_2)}{L} = 0.8692 \text{ x } 41.82 \text{ x } 10^{-6} \text{ x } \frac{(33.5 - 27)}{66x10^{-3}} = 3.58 \text{ x } 10^{-3} \text{ W}$$

or energy flow = Q = 3.58 x 10^{-3} x 70 = 0.251 J

A heat flow and temperature gradient for LDPE/GF (33%) can be similarly generated as in the case of PS/GF (33%) (Figure 8). Equations 1 and 2 for LDPE/GF (33%) are:

$T(l) = 0.00000052x^5 + 0.00007215x^4 + 0.0034x^3 + 0.063876x^2 + 0.56627x + 33.5$

and

$T(l) = -0.00000036x^5 + 0.00005256x^4 - 0.00259x^3 + 0.05128x^2 - 0.50281x + 33.5$

By referring to Figure 3, 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 cm^3 x 1.2 g/ cm^3 = 0.72 g. The microwave power absorbed

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

= 0.72g x 1510 $Jkg^{-1}K^{-1}$ x [(32.5 +273) K – (21 +273) K] = 12.503 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.

Referring to Table 1, the temperatures at different sections of the test pieces were generally higher in PS/GF (33%) sample even it was exposed to shorter microwave irradiation of 60 seconds than LDPE/GF (33%) sample. This is because PS/GF (33%) had a higher loss than LDPE/GF (33%). Referring to Table 2, the thermal energy absorbed by different sections of the test pieces were generally higher in PS/GF (33%) sample even it was exposed to shorter microwave irradiation of 60 seconds than LDPE/GF (33%) sample. The reason is the same as above.

7. Lap shear strength and temperature distribution 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 [11]. Figure 9 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^2, at this exposure duration exceeded that obtained by ambient conditions curing by 17%, but the time required was a mere of 0.2% of its counterpart [12, 13]. 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 (Figure 10), the maximum lap shear strength was 331 N/cm^2 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 0.08% of its rival [11, 13]. 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 [12].

Figure 9 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. Figure 10 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.

8. Lap shear strength and temperature distribution for LDPE/GF (33%)

Figure 11 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^2 (line 800PE1 in Figure 11); 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^2 (line 800PE2 in Figure 11) [12, 14, 15]. In both cases, the results obtained were similar to the

work of another researcher using high-density polyethylene [16]. Referring to Figure 12, it is found that 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 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^2). When compared with the ambient cured samples, the increase in lap shear strength was 45 % [18]. 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 12 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 an average value of 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 was significant enough to cure the Araldite rapidly [18]. Exposure times of over 240 seconds will deform the samples.

Conclusion

By comparing the heat distribution and lap shear strength of two random glass fibre reinforced thermoplastic matrix composite materials, PS/GF (33%) and LDPE/GF (33%), it can see 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.

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Figure 1: Microwave Facilities Configuration

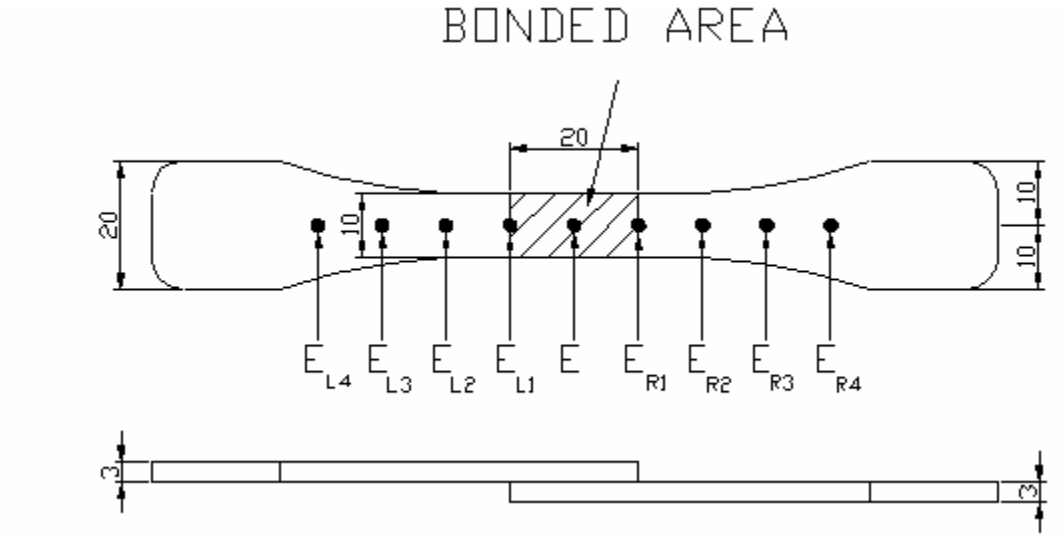

Figure 2: Locations at which temperature measurements (in the sample) are taken

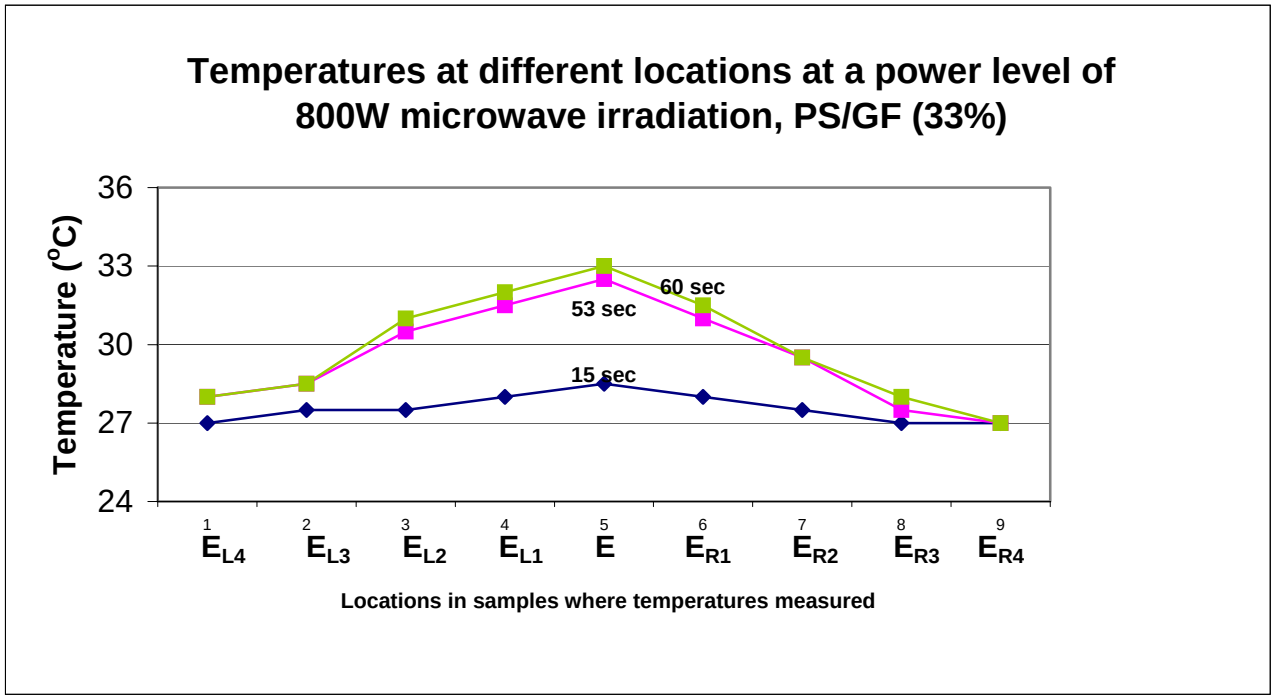

Figure 3: Temperature at different locations in samples with different exposure duration to 800 W microwave irradiation

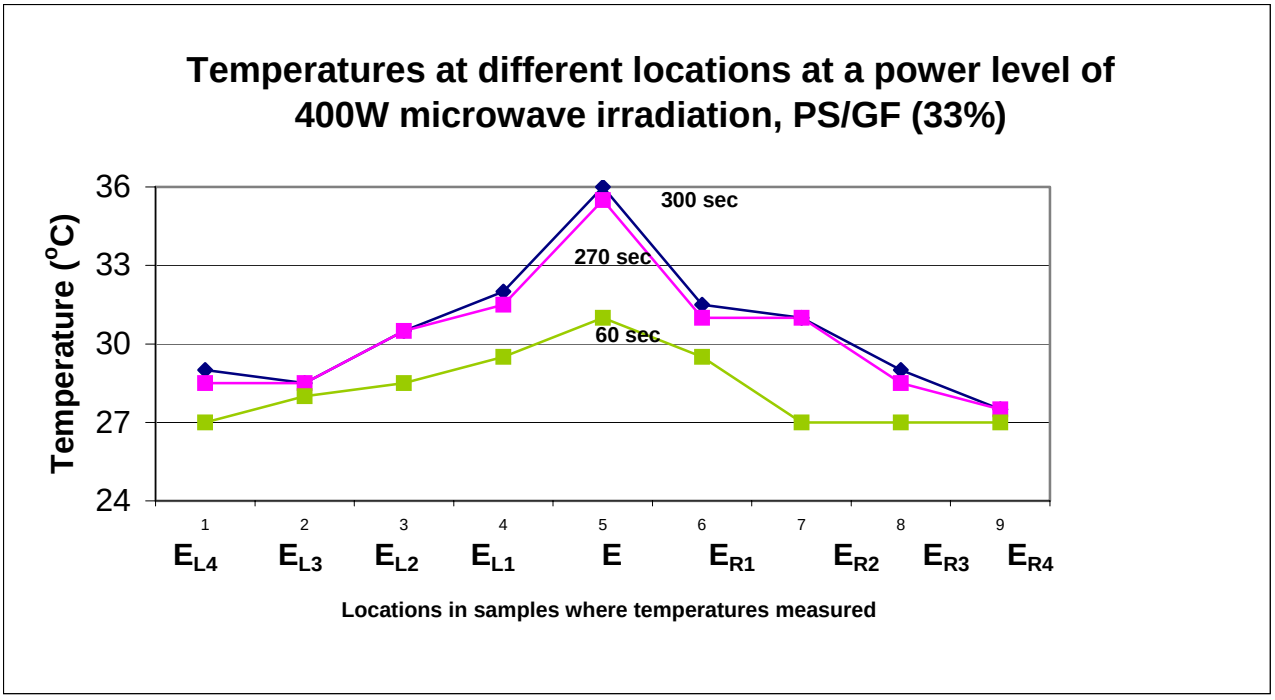

Figure 4: Temperature at different locations in samples with different exposure duration to 400 W microwave irradiation

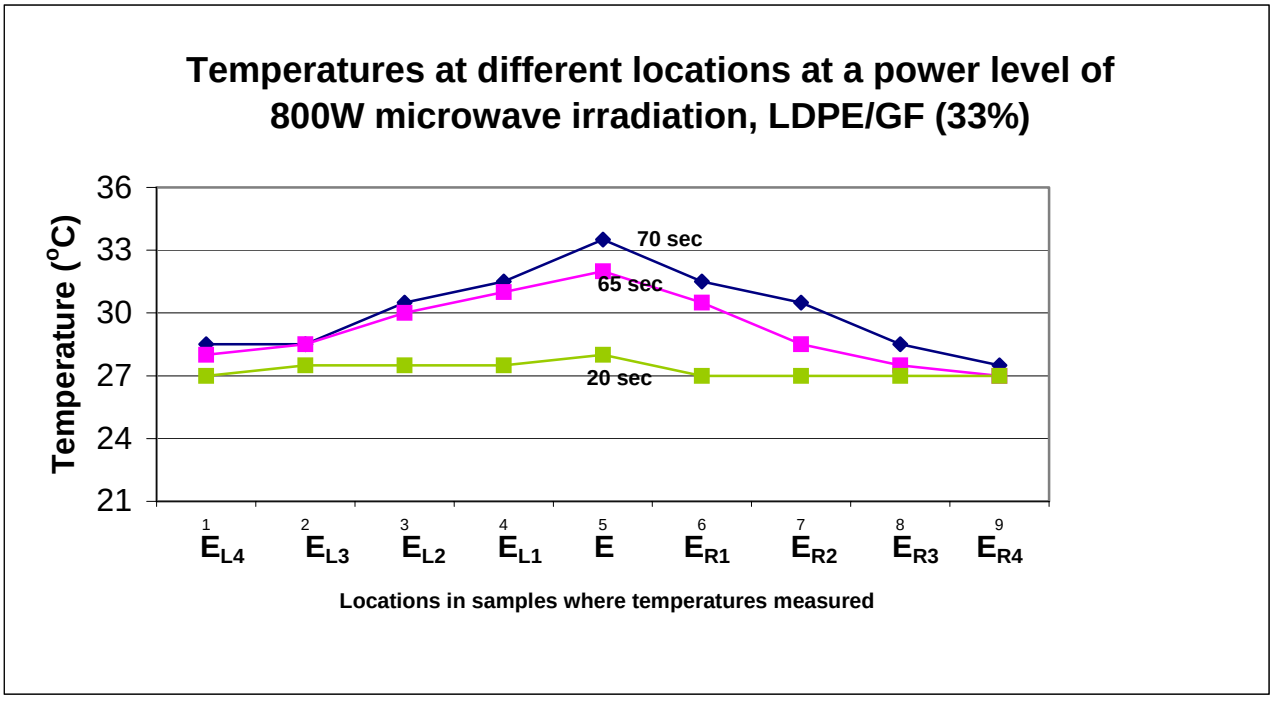

Figure 5: Temperature at different locations in samples with different exposure duration to 800 W microwave irradiation

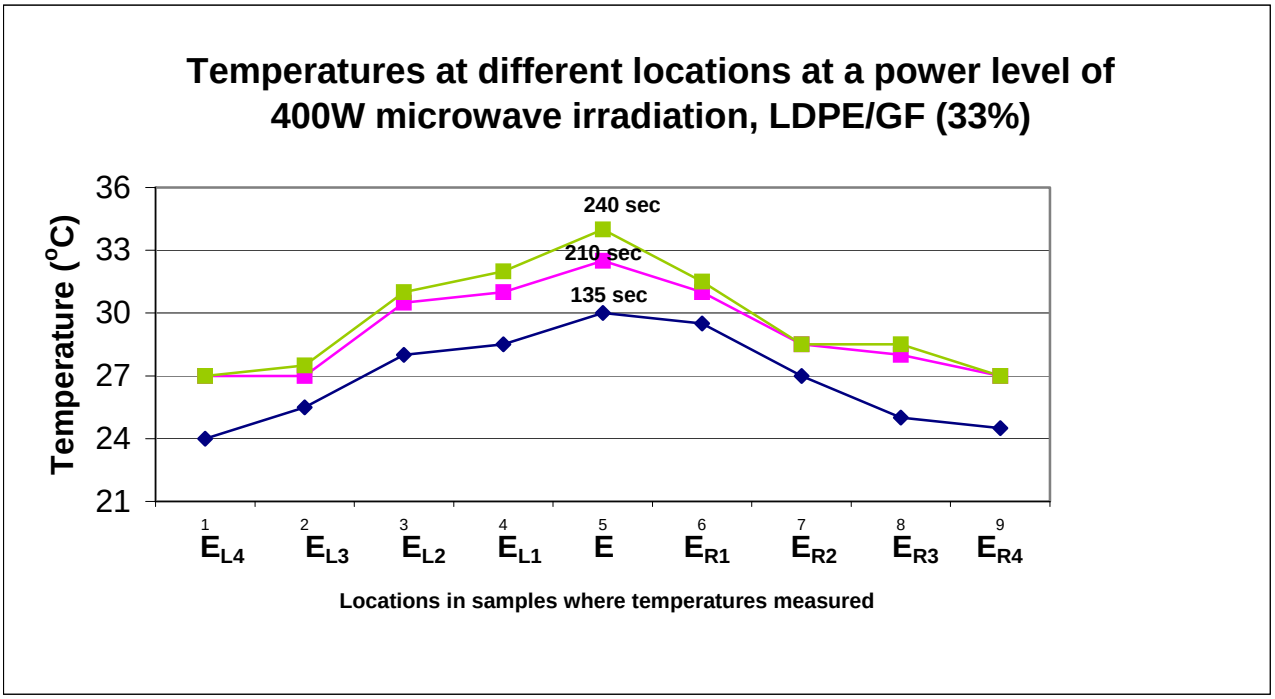

Figure 6: Temperature at different locations in samples with different exposure duration to 400 W microwave irradiation

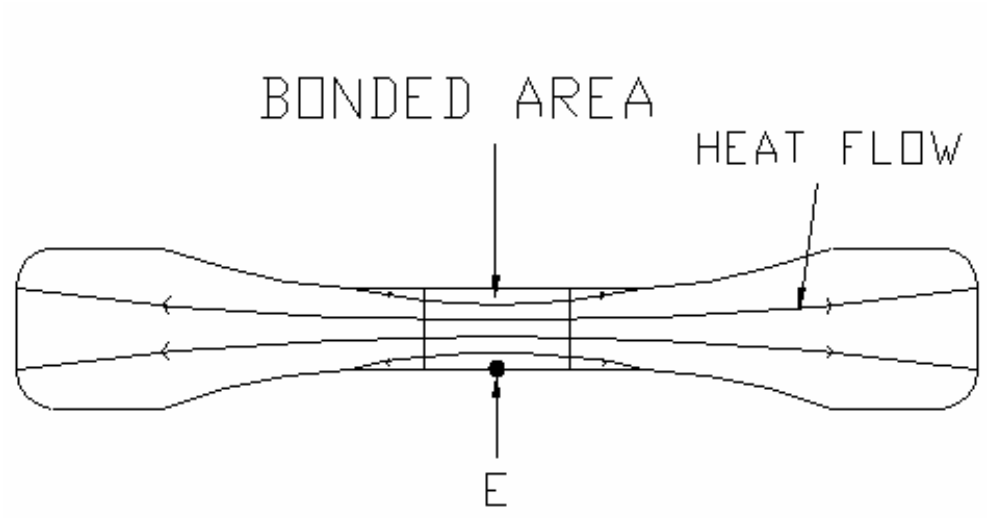

Figure7: Heat flow in the test pieces

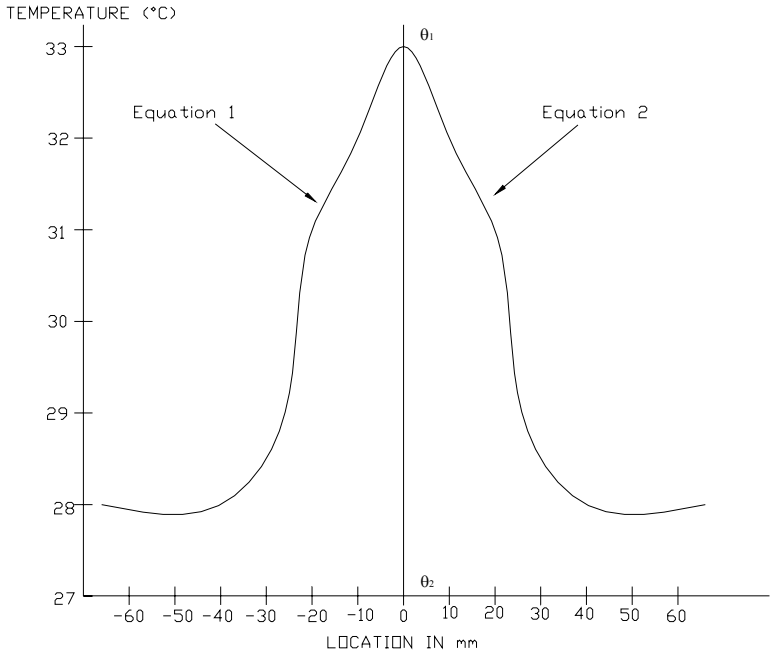

Figure 8: Heat flow and temperature gradient of PS/GF (33%) test pieces exposed to a power level of 800 W and a duration of 60 seconds.

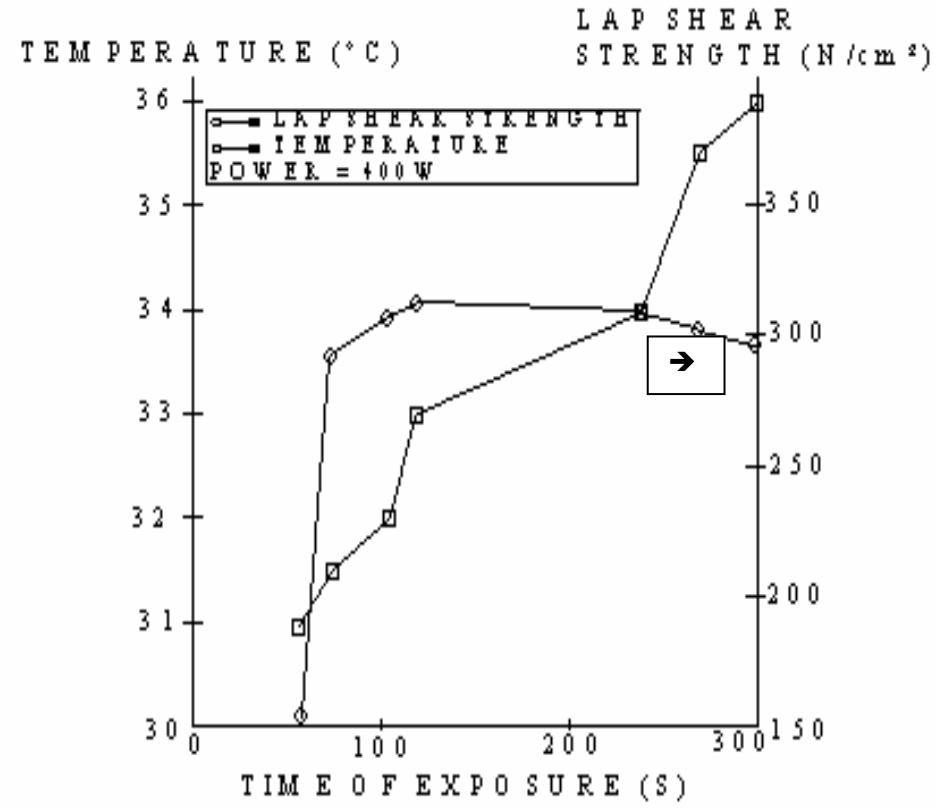

Figure 9: Lap shear bond strength and temperature against time of exposure to microwaves of 400W in the samples of PS/GF (33%)

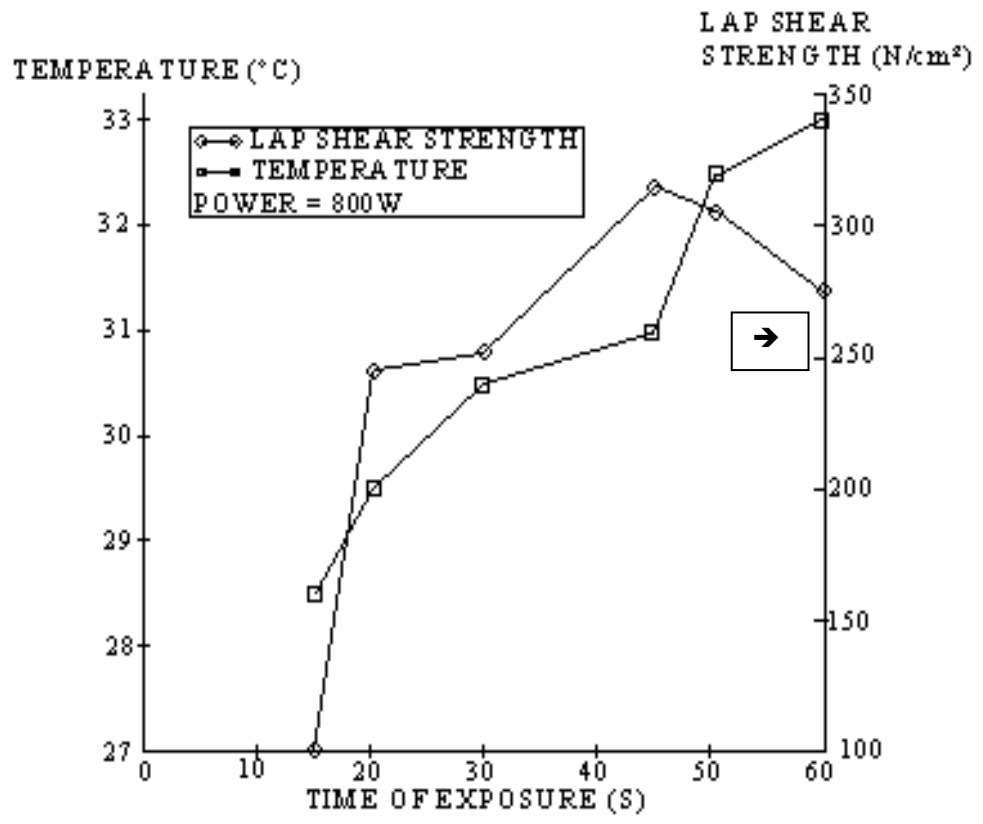

Figure 10: Lap shear bond strength and temperature against time of exposure to microwaves of 800W in the samples of PS/GF (33%)

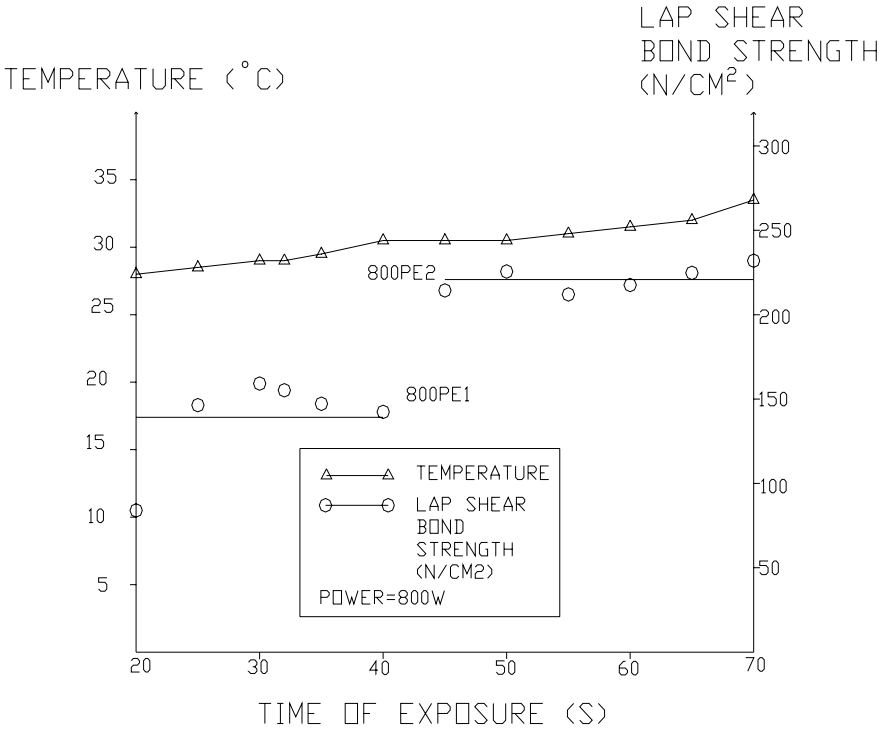

Figure 11: Lap shear bond strength and temperature against time of exposure to microwaves of 800W in the samples of LDPE/GF (33%)

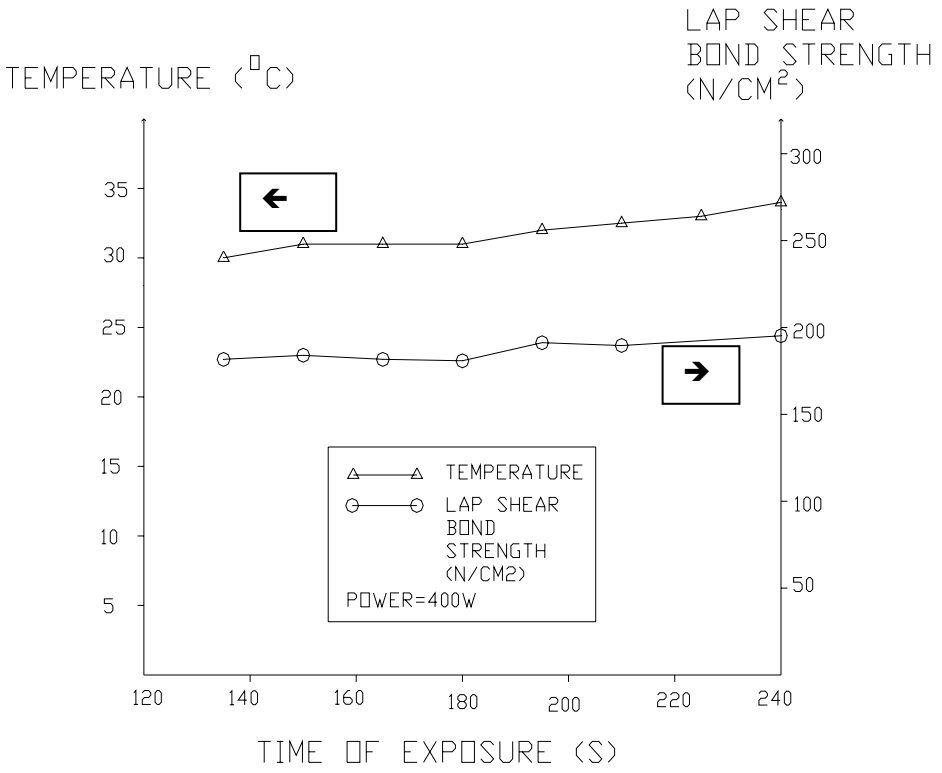

Figure 12: Lap shear bond strength and temperature against time of exposure to microwaves of 400W in the samples of LDPE/GF (33%)

Table 1: Volume and Average Temperature of Different Sections of LDPE/GF (33%) PS/GF (33%) Test Pieces respectively

Sections	Volume (mm^3)	Average temperature (^oC) for LDPE/GF (33%) samples	Average temperature (^oC) for PS/GF (33%) samples
Rest on left	1600	27	27.5
E_{L4} and E_{L3}	300	27.75	28.25
E_{L3} and E_{L2}	300	29.5	29.75
E_{L2} and E_{L1}	300	31	31.5
E_{L1} and E	600	32.5	32.25
E and E_{R1}	600	32.5	32.25
E_{R1} and E_{R2}	300	31	31.5
E_{R2} and E_{R3}	300	29.5	29.75
E_{R3} and E_{R4}	300	28	28.25
Rest on right	1600	27	27.5

Table 2: Mass and Energy of Different Sections of LDPE/GF (33%) PS/GF (33%) Test Pieces respectively

Sections	Mass (g)	Energy absorbed (J) for LDPE/GF (33%)	Mass (g)	Energy absorbed (J) for PS/GF (33%)
Rest on left	1.92	13.553	2.53	17.845
E_{L4} and E_{L3}	0.36	2.835	0.47	3.700
E_{L3} and E_{L2}	0.36	3.421	0.47	4.466
E_{L2} and E_{L1}	0.36	4.105	0.47	5.405
E_{L1} and E	0.72	12.503	0.95	11.339
E and E_{R1}	0.72	12.503	0.95	11.339
E_{R1} and E_{R2}	0.36	4.105	0.47	5.405
E_{R2} and E_{R3}	0.36	3.421	0.47	4.466
E_{R3} and E_{R4}	0.36	2.835	0.47	3.700
Rest on right	1.92	13.553	2.53	17.845