Permittivity Measurement of Thermoplastic Composites at Elevated Temperature.

*H S Ku[#,+],B Horsfield[#], J A R Ball[##] and E Siores**

[#] Faculty of Engineering and Surveying, University of Southern Queensland.
[+] PhD Graduate, Swinburne University of Technology, Australia.
Associate Professor and Head, Electrical, Electronic and Computer Engineering, University of Southern Queensland, Australia.
* Professor and Executive Director, Industrial Research Institute, Swinburne, Swinburne University of Technology, Australia.

Manuscript Number: 605

Corresponding Author:

Title	: Dr.
Name	: Harry Siu-lung **KU** (Corresponding author)
Affiliation	: Faculty of Engineering and Surveying, University of Southern Queensland.
Tel. No.	: (07) 4631-2919
Fax. No.	: (07) 4631-2526
E-mail	: ku@usq.edu.au
Address	: Faculty of Engineering and Surveying, University of Southern Queensland, West Street, Toowoomba, 4350, Australia.

Abstract: 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 $\delta = \varepsilon''/ \varepsilon'$. This paper describes two convenient laboratory based methods to obtain ε', ε'' and hence tan δ of fibre-reinforced thermoplastic (FRTP) composites. One method employs a microwave network analyser in conjunction with a waveguide transmission technique, chosen because it provides the widest possible frequency range with high accuracy. The values of the dielectric constant and dielectric loss of glass fibre reinforced (33%) low density polyethylene, LDPE/GF (33%), polystyrene, PS/GF (33%), and Nylon 66/GF (33%), were obtained. Results are compared with those obtained by another method using a high-temperature dielectric probe.

INTRODUCTION

The use of microwave high-energy rate joining of fibre-reinforced thermoplastic (FRTP) composites has shown promising preliminary results (Ku et al, 1997a; 1997b; 1998) and more research is being carried out so that the technology can find applications in manufacturing industries in the near future. The dielectric constant, ε', and the loss tangent, tan δ, of FRTP composites have rarely been reported in the literature and furthermore the published data were at room temperature only (Osswald and Meng, 1995; Lynch, 1975; Shackelford, 1992). As these electrical properties vary significantly with rising temperatures and frequency, values obtained at room temperature may not be appropriately used to predict the microwave-reactiveness of thermoplastic composites at elevated temperatures. Extensive methods (Ness, 1983; Sabburg et al, 1992; Senko, 1997) have been reported in the literature for the measurement of ε values of materials. A one-port network analyser reflection measurement (Sequeria, 1991) on multiple length samples was employed to find both ε and μ. An in-situ monopole antenna probe and a numerical technique (Pham, 1991) which extends the measurement frequency range for the measurement of ε was also developed. Ness (1983; 1985) used two-port transmission measurements made by a semi-automatic network analyser via co-axial line and waveguide and the same method was used to accurately measure the ε values of several types of Australian soil and this is the basis for the measurement system used in this paper (Sabburg, et al., 1992). This paper starts by showing the relationship between the depth of penetration of microwave energy into a material under test and its complex relative permittivity and loss tangent. It also describes the measurement of ε' and tan δ of three types of random, 33% by weight, glass-fibre reinforced thermoplastic composites, and of three kinds of Araldites used as priming agents in the welding of the three types of fibreglass reinforced material by microwave energy. The three thermoplastic matrices chosen for the study are the three most commonly used thermoplastics, namely, low density polyethylene (LDPE), polystyrene (PS) and Nylon 66. The heat resistance limitation of the microwave network analyser used prevents measurement of the complex relative permittivity at temperatures higher than 100^{o}C. The frequency band ranged from 2.2 GHz to 12.5 GHz, which covers most of the industrial applications band for microwaves.

MATERIALS AND METHODS

Reflection Coefficient and Depth of Penetration

It can be shown that for relatively low loss materials, the reflection coefficient is given by

$$\rho \approx \frac{-(\sqrt{\varepsilon'}-1)}{(\sqrt{\varepsilon'}+1)} \qquad (1)$$

and the depth of penetration is

$$D \approx \frac{\sqrt{\varepsilon'}}{\omega\sqrt{\mu_0 \varepsilon_0 \varepsilon''}} \text{ for } \tan\delta << 1 \qquad (2)$$

where ω is the angular frequency;

μ_o is the permeability in air;

ε_o is the permittivity of air.

The depth of penetration is defined as the distance from the surface at which the power density has fallen to 0.368 of the value immediately below the surface. Equation 1 implies that reflection coefficient increases with ε' and when ε' is very large, $|\rho| \rightarrow 1$ i.e. total reflection. The negative value for ρ signifies that the transmission coefficient for dielectric field entering the sample. $\tau = 1 + \rho$ is less than unity. Equation 2 illustrates that for good penetration, ε' should be large and ω and ε'' should be small i.e. small loss tangent. In short, the reflection coefficient increases with ε' and the penetration depth of the material increases with ε'. So, a sample with high ε' will reflect more of the incident energy, but the energy, which enters the sample, will penetrate further (than in a sample having the same ε'' but lower ε').

Theory of Waveguide Transmission Technique

A waveguide transmission technique is a convenient laboratory based method, which employs a network analyser to obtain the ε values of a length of sample filled waveguide. The ε value was calculated at spot frequencies off-line from manual readout of limited transmission coefficient, $S_{21,}$ data from the network analyser. Since the transcendental equation used in the off-line calculation had multiple solutions, the broadband S_{21} data was used as a check on the calculated ε values. From this measurement the sample dielectric constant, dielectric loss and loss tangent were calculated. During measurements, fixed lengths of waveguide were filled with the FRTP and a range of waveguide sizes was required to provide an almost continuous spectrum of frequencies from 2.2 - 12.5 GHz. Details of the theory can be found in the work of Sabburg (1992). The calculated values of S_{21} were compared with the measured data and ε' was adjusted until the phase angles agreed. After that tan δ was adjusted until the magnitudes matched. The cycle was repeated until the error was minimum. The process was cumbersome and tedious and computer software was therefore developed to speed up the procedure. The software requested the input of values of transmission coefficients and of those of three markers, (one particular set is summarised in Table 1 for ease of reference) as well as the broadside dimension of the waveguide, and the sample length, L for the initial estimate of ε′ for the sample. An accurate initial estimate of ε′ is important because it enables the iteration process to converge to the required result from the infinite number of solutions. Occasionally, the software failed to estimate the initial value of ε′ and the programme did not converge. In this situation, a manual estimate was required.

Waveguide Sizes and Sample Lengths

In order to cover the frequency range from 2.2 to 12.5 GHz, four different sizes of waveguides were used, namely: WR90, WR159, WR229 and WR340. Taking waveguide WR340 as an example, the recommended range of frequencies (HP Microwave Measurement Handbook, 1993) for single (TM_{10}) mode only was from 1.8 to 3.3 GHz. To obtain satisfactory results from the waveguide transmission technique, the sample length must be at least three quarters of a guide wavelength at the highest measured frequency. The wavelength in the sample depends on the sample relative permittivity or dielectric constant, ε′, (Kraus, 1992) as follows :

$$\lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon'}} \frac{1}{\sqrt{1-(\frac{\lambda_o}{2a\sqrt{\varepsilon'}})^2}} \qquad (3)$$

where λ_o is the free space wavelength and a is the broad side waveguide dimension. Assuming the largest possible frequency, i.e. frequency = 3.3 GHz, λ_o = 30/3.3 = 9.091cm and a = 3.4 x 2.54 cm = 8.636 cm.

It is expected that the dielectric constant of the sample is in the range of 2 to 5. Assume ε′ = 2 then Equation 3 yields λ_g = 6.926 cm. A software programme was written to calculate the maximum sample length required for each waveguide size. The sample length L_2 with ε′ = 2 would be 5.194 cm or 51.94 mm.

For each waveguide size, the network analyser was calibrated using a short circuit, an offset short and a matched load. In addition to inputting the cut-off (minimum) and maximum frequency to the programme for a particular waveguide size e.g. WR340, it was also necessary to input the delay time for the offset short circuit. The cut-off frequency was then easily calculated from the fact that the cut-off wavelength λ_c (Metaxas and Meredith, 1983) is equal to 2 a where a is the larger cross-sectional dimension of a rectangular waveguide.

Therefore, $f_c = \frac{3x10^8}{\lambda_c}$ =1.7369 GHz. The absolute maximum frequency of operation is that at which the first higher order mode H_{20} will begin to propagate. This is $f_{maximum} = \frac{3x10^8}{a} =$ = 3.4378 GHz. It can be noticed that the values of f_c and $f_{maximum}$ encompass the recommended frequency range of 1.8 - 3.3 GHz for the waveguide of WR340. Also, delay time for offset short circuit = length of offset/velocity of light. Since the length of offset is 35.5 mm, the delay time = 0.11833 ns. Similarly the values of f_c, $f_{maximum}$ and delay time for waveguides of WR229, WR159 and WR90 can be calculated.

Dielectric Probe Method

The dielectric probe method employs an open-ended coaxial line to measure the complex permittivity of materials. The open-ended coaxial probe consists of a truncated section of a coaxial line (Blackham et al., 1991) and an optional extension of a ground plane to improve the contact with the sample under test (NRC, 1994). This was not required for the present series of measurements. The input port of the sensor is connected to the measurement equipment through a coaxial cable. The parameter to be measured is the reflection coefficient at the interface between sensor and sample. The use of an automatic analyser as the measuring instrument significantly simplifies and enhances the accuracy of the measurement procedure. In this series of measurements, a Hewlett Packard HP 85070B dielectric probe was used in conjunction with a HP 8410B network analyser. The system allows measurements of the complex permittivity for a wide range of semi-solid, pliable solid and liquid materials and performs all of the necessary network analyser control, calculation, and data presentation functions. The equipment is convenient to use and the operator needs only to press the probe against (or immerse it in) the MUT (material under test) to obtain a measurement. The software controls the network analyser and measures the complex reflection coefficient of the MUT. It subsequently converts the reflection coefficient into the complex permittivity of the MUT and results are displayed on the screen. The probe must first be calibrated (Blackham et al, 1991) against air, metallic shorting block and pure water before it can be used to measure the ε of any material. Care should be taken to avoid the presence of bubbles beneath the probe while calibrating the kit against pure water. A re-calibration facility is available to speed up the measurements while measuring ε over a range of temperatures varying from -40^{o}C to 200^{o}C. The frequency range is from 200 MHz to 20 GHz. The diameter of the sample under test must be greater than 20 mm and its thickness and flatness must be over $\frac{20}{\varepsilon'^{\frac{1}{2}}}$ and less than 25μm respectively. The accuracy for the ε' and tan δ are $\pm 5\%$ and ± 0.05 respectively. The maximum recommended ε' is less than 100 and the minimum recommended tan δ is 0.05. For high temperature measurement, the probe must be made from materials of very low thermal expansion coefficient.

RESULTS

Results from Waveguide Transmission Technique

In order to verify that the transmission line set-up used measures what it ought to measure, materials with known dielectric constant values were measured; air and

Teflon were chosen for this purpose and their dielectric constants were measured at room temperature. The measured values of the dielectric constants for air and Teflon were 1.0 and 2.0 respectively at room temperature. This coincides very well with data (Metaxas and Meredith, 1983; von Hippel, 1995) in the literature and verifies that the equipment measures what it is supposed to. The dielectric constants and loss of acrylic at room temperature (25^{o}C) and at a frequency of 3 GHz measured by the set-up matched the published data (Metaxas and Meredith, 1983; von Hippel, 1995) of 2.6 and 0.015 respectively.

The first material under test was 33% LDPE/GF (33%). It was found that the values of dielectric constant did not change much with frequency and temperature but a trend was established that the higher the temperature the lower the dielectric constants, particularly at the higher frequency end. As there was no published data for the values of ε′ of LDPE/GF (33%), simulated data was used to verify the authenticity of the measured data. The values (Metaxas and Meredith, 1983; von Hippel, 1995) of ε′ of LDPE (2.25) and glass fibre (3.78) at 25^{o}C and at 3 GHz were employed to generate the ε′ of LDPE/GF (33%) at 25^{o}C and at 3 GHz. It was assumed that the mixture was homogeneous and the ε′ of the material could be calculated by proportion as follows: $2.25 x \frac{67}{100} + 3.78 x \frac{33}{100} = 2.755$. The data measured by the technique at the same physical condition was 2.6 and this showed that the measured data was rational. By similar argument, ε″ could also be simulated and it was found to be 0.0018. This suggested that LDPE/GF (33%) should therefore be a low loss material and its loss tangent was not appropriate to be measured by this method.

The next material to be studied was 33% glass fibre reinforced polystyrene [PS/GF 33%)]. It was also found that the values of dielectric constant did not change much with frequency and temperature, but the dielectric constant tends to be lower at higher temperatures, especially towards the higher frequency end. Values of ε′ and ε″ of PS/GF (33%) were similarly simulated from published data (von Hippel, 1995) and they were found to be 2.92 and 0.0021 respectively at 25^{o}C and at 3 GHz. On the other hand, the measured values at the same conditions were 2.90 and 0.0136 respectively. The measured value of ε′ was very near to the simulated one and seemed to be reasonably accurate; while, the measured value of ε″ was much higher than the simulated one (6.5 times) and it was 7.6 times higher than that of the simulated LDPE/GF (33%). Since the ε″ of PS was low and was very near to that of LDPE, it was therefore concluded that the values obtained were unreliable and further investigations were needed.

The last material to be discussed is Nylon 66/GF (33%) where the higher the values of the temperature, the lower the values of the dielectric constant as depicted in Figure 1. However, the variation of the dielectric constant with frequency exhibits a ‘U’ shape relationship. Initially, the value of the dielectric constant decreases with increasing frequency (from 7 GHz onwards) until a minimum value is reached at certain frequency (around 10 GHz). It then increases with increasing frequency (up to 12 GHz). All of these characteristics are shown in Figure 2. The simulated value of ε′ for Nylon 66/GF (33%) at 10 GHz and at 25^{o}C is 3.28 while that procured by measurement is 3.66; the measured value is 10% higher. The trends of the values of the measured dielectric constant for the three materials were the same and followed the trend for most materials e.g. water (Senko, 1997). Figures 3 and 4 illustrate the change of loss tangent values for Nylon 66/GF (33%) with frequencies and temperatures respectively. The simulated value of tan δ of Nylon 66/GF (33%) at the same ambient conditions is 0.0072 and the measured one is 0.0232; the measured value is 69% larger. This shows that the higher the temperature, the higher the values of the dielectric loss factor, but the variation of the dielectric loss factor with frequency was different. It has a ‘U’ shape relationship as in the case of dielectric constant of Nylon 66 /GF (33%) mentioned above. Since Nylon 66 is a relatively higher loss material, it was reckoned that the values of the loss tangents obtained were reliable. Referring to Figure 3, at a frequency of 7 GHz and at a temperature of 90^{o}C, the loss tangent is at maximum. At this point, the maximum amount of microwave energy penetrated is converted to heat to facilitate the joining process but on the other hand, the dielectric constant is relatively high and microwave energy penetration to the material is not adequate. A compromise value of tan δ and ε′ should therefore be chosen to obtain the greatest microwave energy penetration and maximum energy conversion to heat. Similar arguments can be applied to LDPE/GF (33%) and PS/GF (33%).

Results from Dielectric Probe Method

In order to verify that the equipment measured correctly, materials of known dielectric constant and loss values were first tested; ε′ and ε″ of pure water were therefore measured at the frequency range of 2 - 12.5 GHz and at 25^{o}C. The measured values of ε′ and ε″ of pure water at 25^{o}C and at 2 GHz and at 12.5 GHz were tabled with those of published data in Table 2. From this table it is found that there is some discrepancy in values between the measured and the published data (Senko, H., 1996; Metaxas and Meredith, 1983; von Hippel 1995), but the variation did not suggest that results were erroneous.

LDPE/GF (33%) was tested over a wide band of 2 - 12.5 GHz and a narrow band of 2.2 - 2.5 GHz, both at room temperature. The material was cut into a diameter of larger than 20mm and a thickness (HP85070B Technical Data Sheets, 1993; HP 85070A Technical data Sheets, 1990) of $\frac{20}{\varepsilon'^{\frac{1}{2}}}$ as the ε′ of LDPE/GF (33%) was 2.6, the thickness was made larger than 12.54 mm. Results of ε′ and tan δ of LDPE/GF (33%) are tabulated in Tables 3 and 4 respectively. Over the frequency range of 2-

12.5 GHz, the probe measurements gave values of ε′ from 2.69 in the lower frequency range to 2.61 at the higher frequency end; the values obtained were not too far away from those obtained by its counterpart but tended to be lower at higher frequencies. As to the tan δ, the values increased progressively with frequencies; at or above 5 GHz the values were over 0.05 which was considered valid (HP85070B Technical Data Sheets, 1993; HP 85070A Technical data Sheets, 1990) as far as probe measurements were concerned but the values were higher than those obtained using the simulated value of 0.0007 and were regarded as unreliable since it was known that LDPE/GF (33%) was a low loss material. Over the narrow frequency range of 2.2 - 2.5 GHz, the ε′ values were almost constant at 2.74. The values of tan δ were considered not valid within the said narrow frequency range.

Another material under test was PS/GF (33%) and the results of ε′ and tan δ over a frequency range of 2 - 12.5 GHz are tabulated in Tables 3 and 4 respectively. The ε′ values varied from 3.1 at lower frequencies to 2.95 at higher frequencies, which was slightly higher than both the simulated values and those obtained by the waveguide transmission technique. The tan δ values above 6 GHz were found to be valid (HP85070B Technical Data Sheets, 1993; HP 85070A Technical data Sheets, 1990) as far as the probe kit method was concerned but they were relatively higher in reality and thus they were not accepted.

The next material to be discussed is the two-part five-minute rapid Araldite, a primer used in the joining process of the composites. It was considered in two forms: liquid rapid Araldite (LRA) and cured rapid Araldite (CRA). In both cases, the two parts of Araldite were mixed and then poured into cylindrical aluminium tubes with an internal diameter of 22 mm and a thickness of larger than $\frac{20}{\varepsilon_a'^{\frac{1}{2}}}$ mm (HP85070B Technical Data Sheets, 1993; HP 85070A Technical data Sheets, 1990), where ε_a' is the dielectric constant of the cured rapid Araldite from literature (Metaxas, 1983; von

Hippel, 1995). The cured samples were prepared several days before the measurements but they were still in semi-solid form during the test and cling wrap, a thin film of LDPE, was placed on top of the cylindrical aluminium tubes to prevent the probe making direct contact with the material. They were tested in semi-solid conditions and when the probe was applied on the specimens, the surfaces were deformed and became much smoother so that the required parameters could be measured correctly (HP85070B Technical Data Sheets, 1993; HP 85070A Technical data Sheets, 1990). The liquid samples were poured into the aluminium cylinders immediately prior to commencing measurements and again cling wrap was used to cover the top end of the cylinders. The values of ε' of LRA decreased with increasing frequencies while those of tan δ increased with increasing frequencies and they are shown in Tables 3 and 4 respectively. This implies that processing at higher frequencies favours the process. It was found that the ε' values of CRA were lower than those of LRA and this means that microwaves entering the material penetrate further into the material when the Araldite was in liquid form. Further, tan δ values of LRA were much higher than that in the fully cured specimen suggesting that more energy penetrated into the material was converted into heat. The process can be self-limiting while it is in liquid form. There will be more heating when it is in liquid form. On the other hand, there will be less heating while it is cured. Temperature can therefore fall if the power is fixed. On account of the above behaviour, it is logical to conclude that the microwave processing time should be short to ensure that the Araldite is not cured before the end of the processing cycle as its liquid form favours the process.

Another material tested was rapid tertiary Araldite, which was both in the liquid and the cured form. The two parts of the Araldite were mixed and then poured into the aluminium cylinders. The values of ε' of liquid rapid tertiary Araldite (LRTA) were found to be similar to those of LRA but the values of tan δ of it were up to 50% lower than those of LRA. However, the trend obtained was the same; values became larger as frequency increased. As to cured rapid tertiary Araldite (CRTA), the values of ε′ and tan δ were found to be similar to those of CRA.

The last filler material to be discussed was the high strength Araldite which again was tested in two forms; liquid and cured. The values of ε′ and tan δ of liquid high strength Araldite (LHSA) and cured high strength Araldite (CHSA) were found to be more or less the same. This may be due to the fact that even after days of curing, the CHSA was not fully cured and retained its liquid form electrical properties. However, their tan δ values were much lower than those of LRA, and LHSA was considered to be not so suitable as a primer in microwave processing.

DISCUSSION - WAVEGUIDE TRANSMISSION TECHNIQUE VERSUS DIELECTRIC PROBE METHOD

Figure 5 shows the values of ε′ of LDPE/GF (33%) of the two methods plotted together over the frequency range of 2 - 12.5 GHz and at room temperature. Results match very well but were lower than the simulated value of 2.755. Figure 6 shows the values of ε′ of PS/GF (33%) of the two methods plotted together over the frequency range of 2 - 12.5 GHz and at room temperature. The dielectric probe results were higher than those obtained by the waveguide transmission technique, particularly in the lower frequency range but still much lower than the simulated values.

The waveguide transmission technique accurately measured the ε′ and ε″ values of several commonly used materials like Teflon, air, LDPE/GF (33%) and PS/GF (33%). The situation was the same for the probe kit except in the case of pure water. Even though it seems that the waveguide transmission technique (Blackham et al., 1991) produced more accurate values of ε′ of PS/GF (33%), there is no solid evidence to prove that it is better than its counterpart in industrial applications. It is more complicated and needs many sizes of waveguide to measure values of ε′ over a range of frequencies e.g. 2 - 20 GHz. The dielectric probe was found to be easy to use; sample preparation was also easier and the re-calibration facility made re-calibration at each temperature of measurement affordable. If the accuracy required for the values of ε′ and tan δ is not too significant, like in the case of microwave processing, then the dielectric probe can be chosen. The HP probe kit was designed for measuring the ε′ and tan δ values at elevated temperatures up to 200^{o}C and over a range of frequencies, from 200 MHz to 20 GHz.

CONCLUSION

From the measured data of LDPE/GF (33%), PS/GF (33%) and nylon 66/GF (33%), it is found that at higher temperatures and higher frequencies, these materials become less reflective and permit more microwave energy to enter them. At the same time, the dielectric loss factor increases with temperature and frequency and enables more of the absorbed energy to be converted to heat. Therefore, within limits, higher temperatures and higher frequencies are more suitable for microwave-assisted joining of the three materials. As to the primer/filler, liquid rapid Araldite was found to be the most favourable for the microwave-assisted joining of FRTP composites because of its higher values of loss tangent. The dielectric probe method is the recommended technique to use for measurements of ε′ and tan δ in microwave joining of materials. But, for low loss materials, the values of tan δ should be acquired through the resonant cavity method (Garner et al, 1990; NRC, 1994).

REFERENCES:

Blackham, D., David, F., and Engelder, D., (1991) High Frequency Dielectric Materials Measurements, RF & Microwave Measurement Symposium and Exhibition, Hewlett Packard Company.

Garner, H.R., et al (1990), Measurement of Permittivity at Elevated Temperatures Using Cavity Perturbation and CO_2 Laser Irradiation, Rev. Sci. Instrum. 61(7), July, pp. 1832-4.

Glazier, E.V.D. and Lamont, H.R.L., (1958) Transmission and Propagation, The Services' Textbook of Radio, Volume 5, London, Her Majesty's Stationery Office, pp. 6, 17, 34, 134-5, 151-7, 174-7, 197 - 9.

HP85070A Dielectric Probe Kit, 200 MHz to 20 GHz, (1990) Hewlett Packard Product Technical Data Sheets, August.

HP8410B Automating the HP 8410B Microwave Network Analyzer, (1980) Hewlett Packard Product Information, June, pp. 5 -10.

HP Coaxial and Waveguide Catalogue and Microwave Measurement Handbook, (1993).

Ku, H.S., Siores E., and Ball J.A.R. (1997a) Weldability and Heat Affected Zone (HAZ) Evaluation for High Energy Rate Joining of Thermoplastic Composites Using Microwave, Proceedings of the Eleventh International Conference on Composite Materials, Gold Coast Australia, 14-18 July, Vol. 6 pp 55-64.

Ku, H.S., Siores E., and Ball J.A.R. (1997b) Welding of Thermoplastic Composites Using Microwave Energy, Proceedings of CIPR International Symposium Hong Kong, 21-22 August, Vol. 2, pp. 612-9.

Ku, H.S., Siores, E., Ball, J.A.R. and Horsfield, B. (1998), An Important Step in Microwave Processing of Materials: Permittivity Measurements of Thermoplastic Composites at Elevated Temperatures, Proceedings of 1998 Pacific Conference on Manufacturing, Brisbane, Australia, August 18-20, pp. 68 – 73.

Kraus, J.D., (1992), Electromagnetics, 4th ed., McGraw-Hill, pp.655-60, 805.

Lynch, C.T. (Ed.), (1975), CRC Handbook of Materials Science, Volume III, Non-metallic Materials and Applications, CRC Press Inc., pp.118 - 120.

Metaxas, A.C. and Meredith, R.J., (1983), Industrial Microwave Heating, Peter Peregrinus Ltd., pp. 28-31, 43, 211, 217, 278, 284-5.

Ness, J., (1983), Broadband Permittivity Measurements at Microwave Frequencies, IREE Conf. Dig., (Australia), September, pp. 330 - 2.

Ness, J., (1985), Broadband Permittivity Measurements Using the Semi-automatic Network Analyser, IEEE Trans. Microwave Theory Tech., Vol. MTT-33, No.11, November, pp.1222 - 6.

NRC (National Research Centre) (1994), Microwave Processing of Materials, National Advisory Board Commission on Engineering and Technical Systems, National Research Council, USA, p.7, 11-2, 100, 105.

Osswald, T.A. and Menges, G., (1995), Materials Science of Polymers for Engineers, Hanser/Gardner Publications Inc., pp. 393-5.

Pham, A.T., (1991), In-situ Materials Permittivity Measurement Using a Monopole Antenna, Proc. IREE Conv., (Australia), Sept., pp. 658 - 61.

Sabburg, J., Ball, J.A.R. and J.B. Ness, Broadband Permittivity Measurements of Wet Soils, Proceedings of 1992 Asia-Pacific Microwave Conference, Adelaide, pp.607 - 10.

Senko, H. and Tran, V.N., (1996), Temperature Control of Microwave Induced Thermal Run-away Using Temperature Derivative Feedback, Proceedings of the International Scientific and Industrial RF and Microwave Application Conference, Melbourne, Australia, 9-10 July.

Sequeira, H.B., (1991), Extracting e and μ of Materials from Vector Reflection Measurements, Microwave Journal Vol. 34 No. 3, March, pp. 73 - 85.

Shackelford, J.F. (Ed.), (1992), The CRC Materials Science and Engineering Handbook, CRC Press, pp. 731 - 9.

von Hippel, A.(Editor), (1995), Dielectric Materials and Applications, Artec House Publishers, pp. 301 - 425.

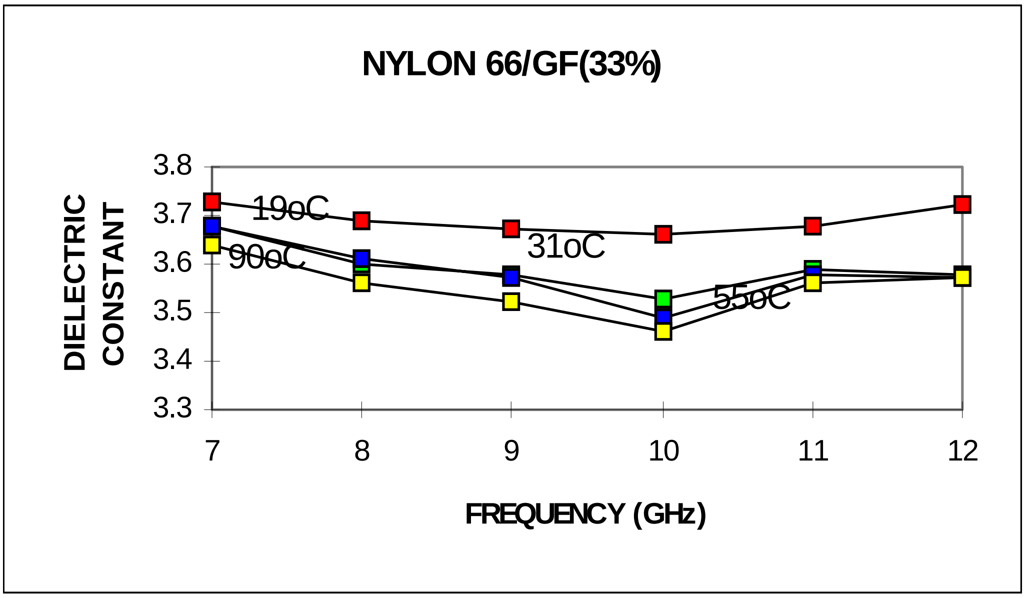

Figure 1. : Dielectric Constants of Nylon 66 /GF (33%) at Elevated Temperatures over a Certain Frequencies.

Author's Name: Harry S KU, et al.
Orientation: Landscape

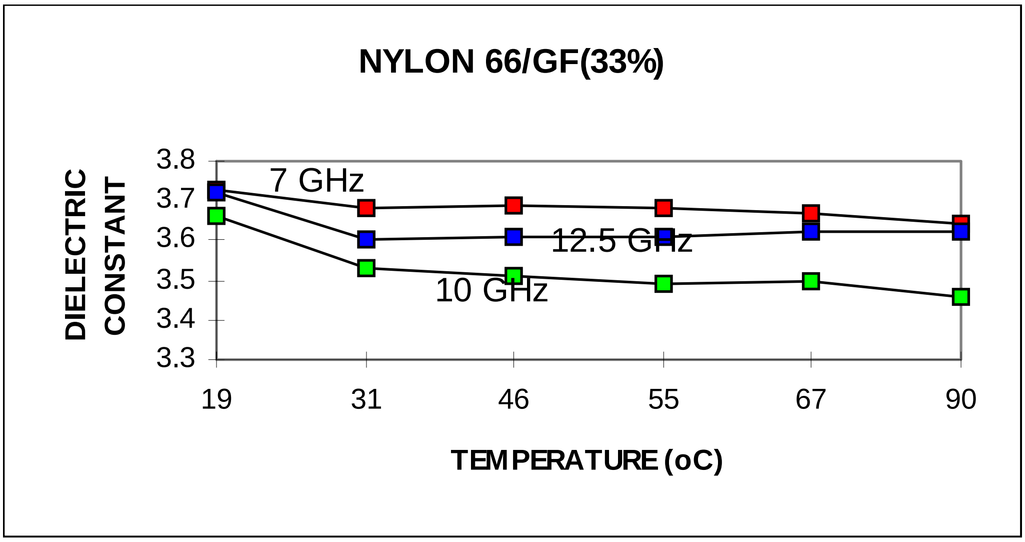

Figure 2. : Dielectric Constants of Nylon 66/GF (33%) at Different Frequencies over a Range of Temperatures.

Author's Name: Harry S KU, et al.
Orientation: Landscape

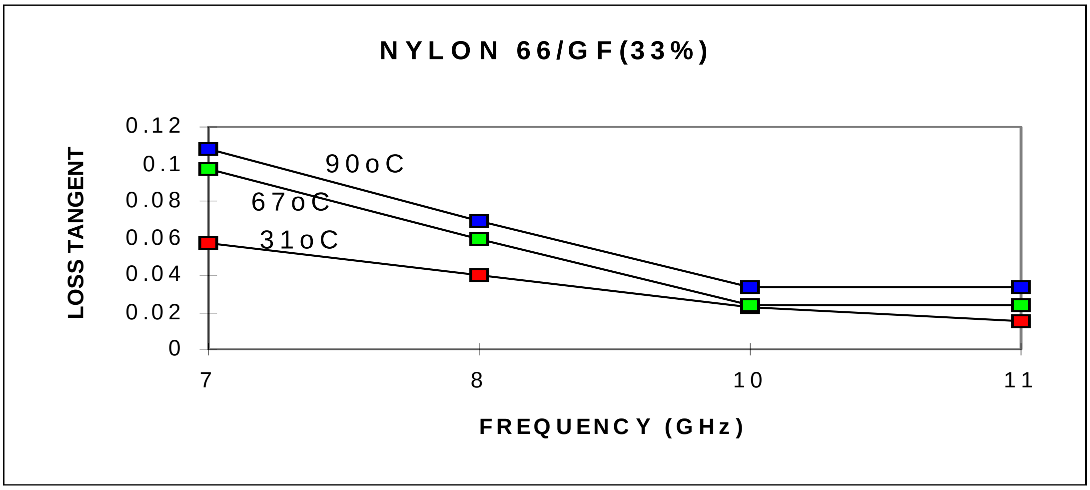

Figure 3. : Dielectric Loss Factors of Nylon 66/ GF (33%) at Elevated Temperatures over Certain Frequencies.

Author's Name: Harry S KU, et al.
Orientation: Landscape

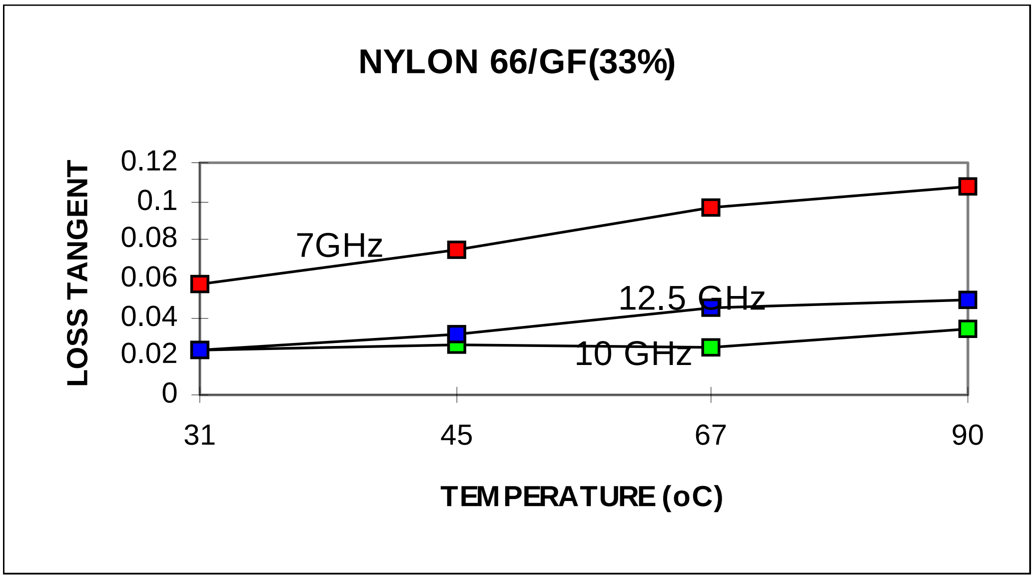

Figure 4. : Dielectric Loss Factors of Nylon66/ GF (33%) at Different Frequencies over a Range of Temperatures.

Author's Name: Harry S KU, et al.
Orientation: Landscape

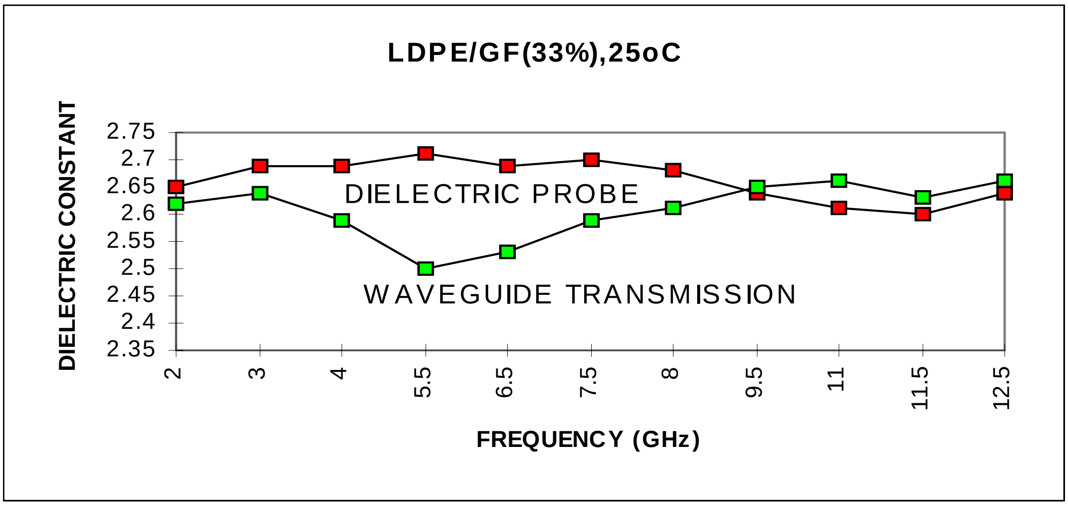

Figure 5. : The Dielectric Constants of LDPE/GF (33%) By Two Methods over a Frequency Range of 2 - 12.5 GHz.

Author's Name: Harry S KU, et al.
Orientation: Landscape

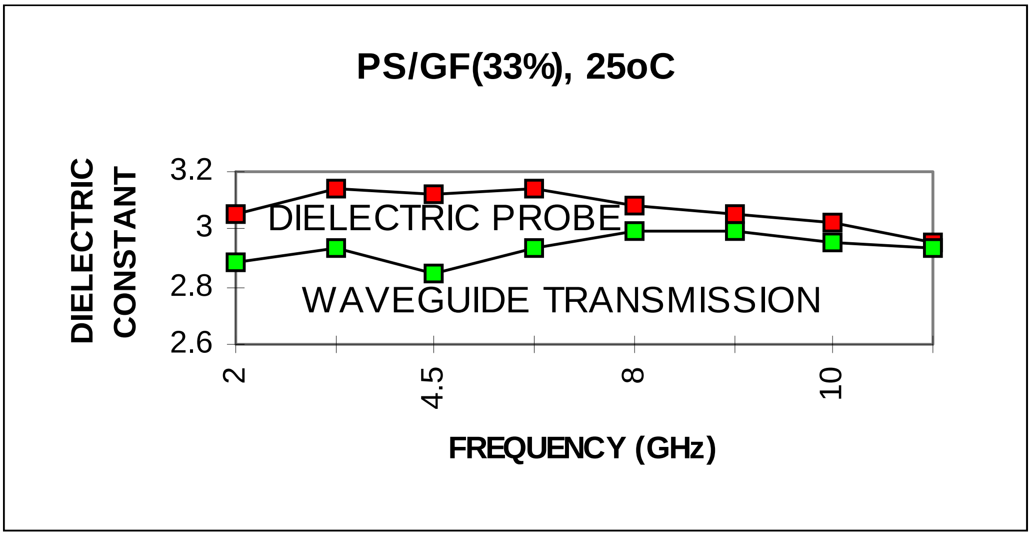

Figure 6. : The Dielectric Constants of PS/GF (33%) By Two Methods over a Frequency Range of 2 - 12.5 GHz.

Author's Name: Harry S KU, et al.
Orientation: Landscape

Table 1. : S_{21} Marker Values for GF/LDPE at 18°C

Marker	Frequency (GHz)	Phase(degrees)	Magnitude (dB)
1	8.528	0.78	-0.326
2	10.148	-90	-1.96
3	11.82	-179.69	-0.228

Table 2. : Dielectric Constant and Loss Values of Pure Water at 25°C

	2 GHz	Values	12.5 GHz	Values
	Measured	Literature	Measured	Literature
Dielectric Constant	77.6	80	56.2	40.8
Dielectric Loss	7.82	6.1	33.4	37.6

Table 3. : Dielectric Constant Values of LDPE/GF(33%), PS/GF(33%), LRA & CRA Over a Wide Band of Frequencies at 25°C

Materials Frequency(GHz)	LDPE/GF(33%)	PS/GF(33%)	LRA	CRA
2	2.65	3.05	2.81	2.41
3	2.69	3.14	2.65	2.39
4	2.69	3.13	2.80	2.58
5	2.68	3.11	2.92	2.45
6	2.69	3.14	2.51	2.40
6.5	2.69	3.10	2.80	2.39
7.5	2.70	3.09	2.58	2.49
8	2.68	3.08	2.59	2.36
9.5	2.64	3.02	2.42	2.33
11	2.61	2.98	2.39	2.33
12.5	2.64	2.95	2.39	2.31

Table 4. : Loss Tangent Values of LDPE/GF(33%), PS/GF(33%), LRA & CRA Over a Wide Band of Frequencies at 25°C

Materials Frequency(GHz)	LDPE/GF(33%)	PS/GF(33%)	LRA	CRA
2	0.014	0.006	0.244	0.060
3	0.012	0.011	0.259	0.064
4	0.031	0.021	0.263	0.070
5	0.049	0.033	0.395	0.082
6	0.052	0.045	0.400	0.086
6.5	0.056	0.050	0.414	0.097
7.5	0.062	0.062	0.413	0.102
8	0.077	0.07	0.413	0.117

9.5	0.081	0.075	0.417	0.106
11	0.099	0.076	0.420	0.142