Parametric Evaluation of Communication Devices in Smart Composite Structures

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Abstract: This paper reports on some of the rheological results of the selected composite materials. The base material components comprise unsaturated polyester (uPE) reinforced with randomly distributed short strands of fibreglass (E type). This material is commonly known as sheet moulding compound (SMC) and is currently used in the automotive industry for different applications. This work will further look into the parameters involved in the processing of the SMC with respect to its visco-elastic behaviour. These parameters involve viscosity, elastic and viscous modulus with respect to the processing temperature. This paper reports on some preliminary results of material processing parameters such as pressures, temperatures, cure times and volume fractions of resins, fillers and reinforcing materials. Also included is an evaluation of the electrical properties of different grades of SMC as a precursor to the encapsulation of a microstrip antenna within the material.

Keywords: SMC, viscous and elastic modulus, rheology, composite, polymer, dielectric constant, permittivity, microstrip antenna, vehicle, automobile, car.

1. Introduction

The use of automobiles is increasing globally particularly in the developing countries of Asia and on average drivers are spending a bigger percentage of their time than ever before in their vehicles. This has resulted in increased demand from vehicle manufacturers to incorporate a large number of communication, guidance and entertainment devices in their new vehicle models. This makes design, testing and manufacture of such vehicles significantly more complex and expensive. It also results in weight increase compared to models that have preceded them.

A number of vehicle manufactures have started developing multi-functional communication devices. Mercedes is currently testing a device that can receive up to 5 specific frequency bands for a number of its communication hardware types [1,2,3]. BMW has developed a device that receives mobile phone frequencies in any country worldwide [4]. Volvo has also created a unit that can receive digital radio, AM, FM and digital TV [5]. However all of these devices are stand alone and are not embedded in vehicles decorative or structural components.

In order to reduce the total vehicle lifecycle cost and deliver on customer demand for entertainment / communication requirements, it is necessary to develop a detailed understanding of the polymeric composite materials to be used in a given application and its interaction between this host material and the communication device. This knowledge can than be used to develop numerical modelling software to be used for simulations of this interaction.

2. Experimental Details

In order to observe the response of viscoelastic behaviour of SMC test samples deformation of SMC in various stress or strain histories was measured. The rheometer used was ARES rotational rheometer with parallel disc of 50 mm diameter. Technique used in the experiment employed small amplitude oscillatory shear. Parameter is the angular frequency, ω = 2πf in rad/s, where frequency f in Hz is defined by [number of cycles per second].

Thus, the shearing rate for the SMC sample is given by Eq (1):

$$\dot{\gamma}(t') = \omega \times \gamma_0 \times \cos(\omega t') \qquad \text{for} \qquad -\infty < t' < t \tag{1}$$

When Eq (1) is expressed in terms of time dependent shear stress (τ_{21}), Eq (2) can be obtained:

$$\tau_{21}(t) = G'(\omega)\gamma_0 \times \sin(\omega t) + G''(\omega)\gamma_0 \times \cos(\omega t) \tag{2}$$

For convenience shear stress can be expressed in terms of an in-phase component with the strain as storage modulus G' and an out-of-phase component as loss modulus G'':

$$G'(\omega) = G_e + \int_o^{\lambda max} H(\lambda) \left[\frac{\omega^2 \times \lambda^2}{(1+\omega^2 \times \lambda^2) \times \frac{d\lambda}{\lambda}} \right] \tag{3}$$

and

$$G''(\omega) = \int_o^{\lambda max} H(\lambda) \left[\frac{\omega \times \lambda}{(1+\omega^2 \times \lambda^2) \times \frac{d\lambda}{\lambda}} \right] \tag{4}$$

The equilibrium modulus G_e is distinguished by $G_e > 0$ for solid materials and $G_e = 0$ for liquids. From equation (3) it can be seen that G_e only effects storage modulus. The above equations are generally valid as long as the strain amplitude, γ_o is sufficiently small [6].

Following procedure was applied to obtain the cure profiles for materials tested: (a) hold test sample at 30 ºC for x1 seconds (conditioning stage), (b) increase temperature to appropriate level in x2 seconds (temperature increase to curing stage), (c) maintain temperature at set level for x3 seconds (curing stage) and (d) reduce temperature to 30 ºC in x4 seconds (cooling down stage). While samples are undergoing these set temperature profiles, observations are recorded for elastic (G') and loss (G'') moduli. Curing cycle schematic is shown in Figure 1. Cure profiles are based on recommendations from the industry partner.

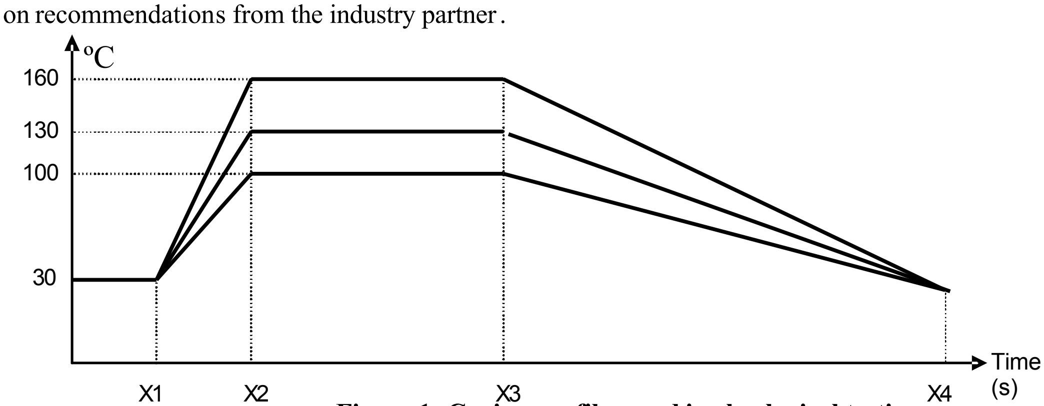

Figure 1: Curing profiles used in rheological testing

3. Experimental Results:

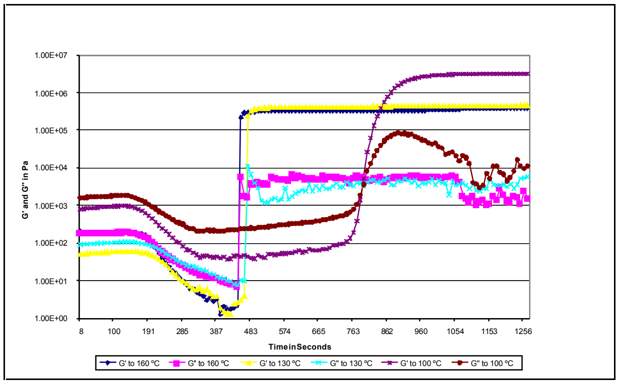

Figure 2. Curing time response to visco elastic modulus for SMC without filler and fibreglass

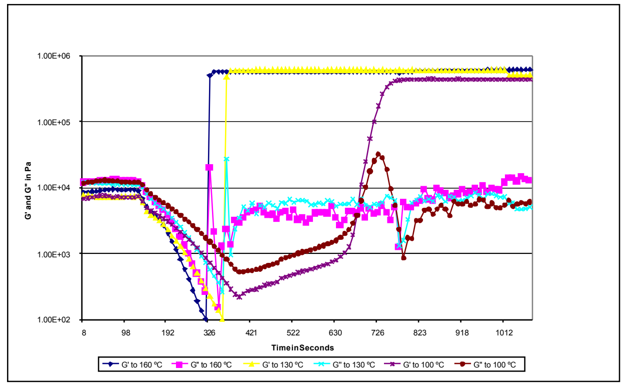

Figure 3. Curing time response to viscous and elastic modulus for SMC without fibreglass

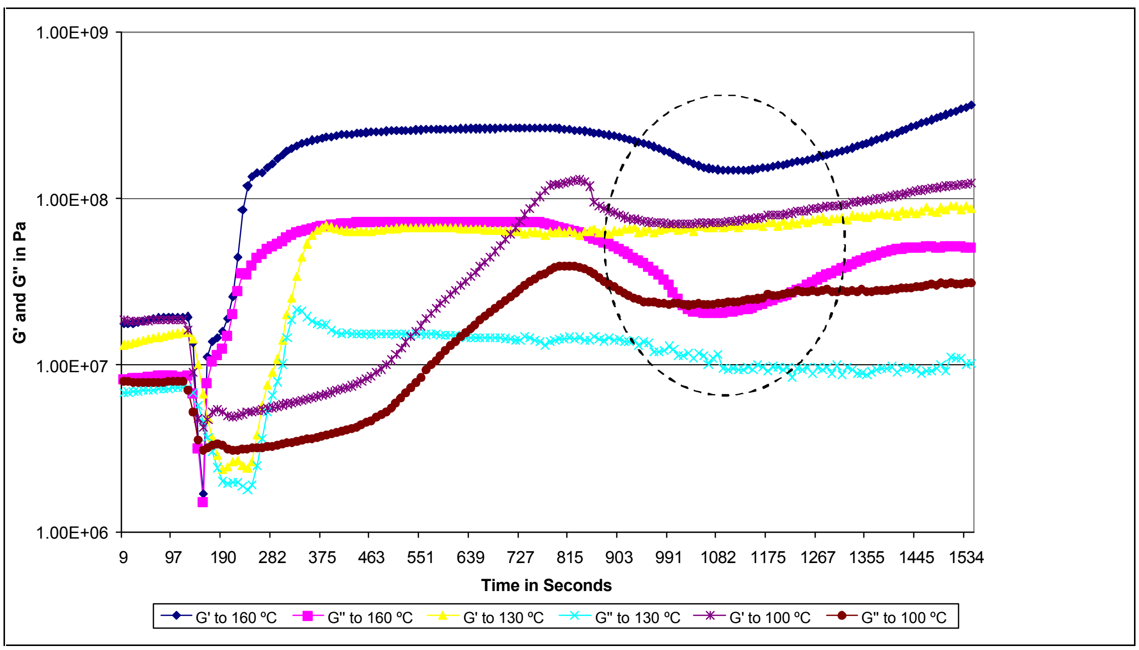

Figure 4. Curing time response to viscous and elastic modulus for SMC

Curing time response of SMC samples are shown in Figures 2 & 3. From these Figures, it is clear that loss modulus G'' dominates in early stage of the curing until cross linking of the structure starts to occur. At this stage there is a crossover of storage modulus G' and loss modulus G'' resulting in storage modulus G' dominating material behaviour after cross-linking. The dip in G' and G'' circled in Figure 4 above is contrary to that expected but can be explained by the possible escape of entrapped gases, created by volatile organic compounds inherent in these polymeric composite materials in its pre-cured state. The evidence for this is corroborated by the voids seen in Figure 5 for samples tested at various temperatures – In Figure 4, the G'' at 160^{o}C appears to show the most significant dip and is consistent with the size of voids seen in Figure 5 for the 160^{o}C sample. These findings might have implications in the shear force distribution on an antenna when cured at several curing temperatures.

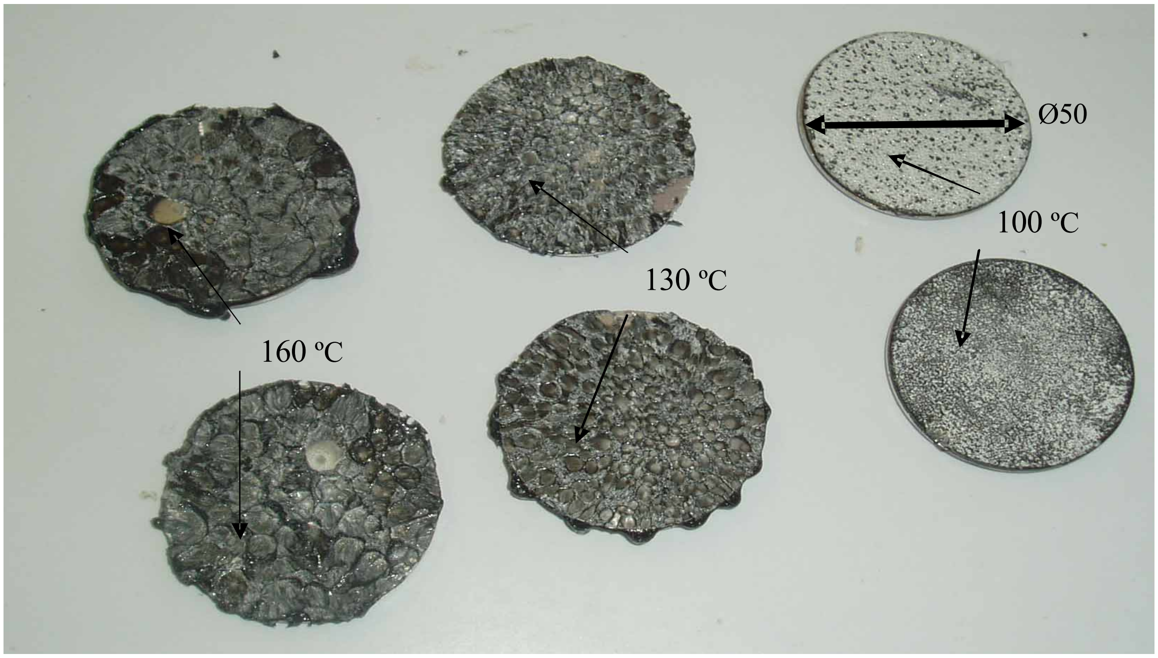

Figure 5. Formation of voids at different cure profiles (all test plates are of Ø 50 mm)

Figure 5 above, shows formation of voids in material during curing. The size of the voids increases as curing temperature increases while number of the voids per unit area decreases at the same time. This can be attributed to the fast curing time at elevated temperatures. Even though, these voids are not necessarily deleterious to the antenna performance, further research might be needed to control the spatial void density within the material matrix.

4. The Microstrip Antenna

Microstrip antennas are an obvious choice for integration in composite structures, primarily due to their low profile and light weight. Typical microstrip antennas can vary in thickness from fractions of a millimetre to several millimetres. Other favourable properties include their conformability, physical ruggedness, capability to produce either linear or circular polarization, as well as being relatively inexpensive [7].

Microstrip antennas consist essentially of a radiating metallic patch sitting on one side of a dielectric substrate, with a metallic ground plane on the other side (see Figure 6). A simple feed line can be etched on the topside of the substrate to guide the electromagnetic wave between the electronic circuit and the antenna. More complex feeds have been devised which improve certain aspects of antenna performance but also increase cost, manufacturing complexity and overall thickness of the antenna.

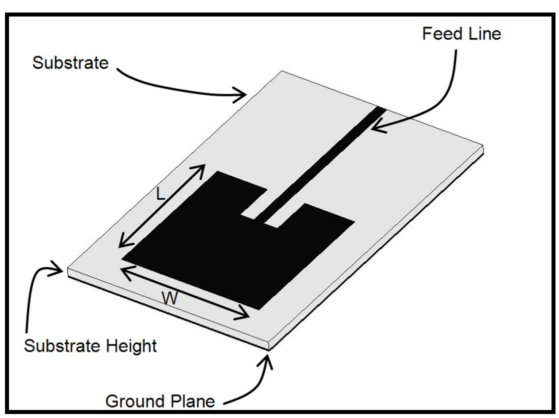

Figure 6 – Anatomy of a microstrip antenna

5. The Dielectric Constant

Before we can design a microstrip antenna, it is crucial to know the properties of the surrounding dielectric material. The Dielectric Constant, ε_r, (also known as permittivity) is a quantity which describes the degree of interaction between an electric field and a electrical charges or dipoles in a dielectric medium, and is a function of frequency, temperature and other parameters. The dielectric constant of the antenna substrate we intend to use is published by the manufacturer in a datasheet because the material is commercially used for this purpose. However, we wish to design an antenna that will be embedded in our composite glass reinforced polymer of unknown dielectric constant.

5.1 The significance of the dielectric constant

When an electromagnetic wave travels through a dielectric its frequency remains constant, but both the speed of propagation and wavelength will decrease as governed by the relationship $\lambda_r = \lambda_0 / \sqrt{\varepsilon_r}$. This change in wavelength requires a change in the dimensions of the antenna because its dimensions are tuned in accordance with the wavelength of interest. It is therefore important to determine the dielectric constant of the composite material as it is imperative to know how much the desired wavelength will be shortened.

5.2 Determination of the dielectric constant of the composite structure

There are many techniques available for the determination of the dielectric constant of a material. Perhaps the most elemental is to sandwich the material under test (MUT) between parallel plates to make a capacitor. A disadvantage of this technique is that it is only effective for frequencies below 1 GHz. A metallic cavity resonator or waveguide measurement can be used, where the system is measured in both the absence and presence of the material. Both of these techniques require rigorous sample preparation and have a restricted frequency range. The technique used is the free space technique illustrated in Figure 7 [8].

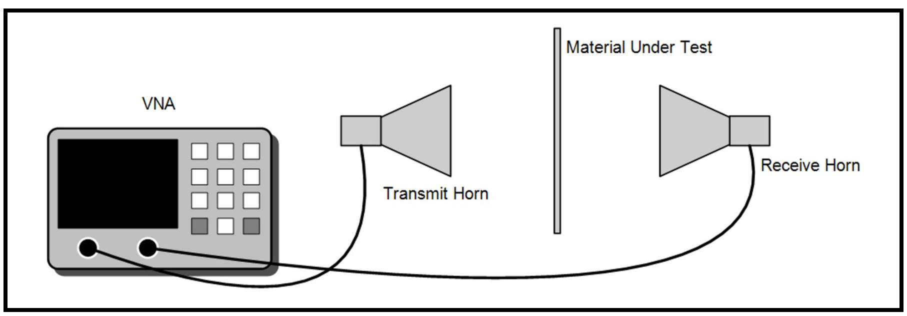

Figure 7 – Illustration of Dielectric Constant test configuration

In this measurement system a Vector Network Analyser (VNA) and a pair of horn antennas are used to measure transmission through a sample. If the material is magnetic, then it is possible to measure reflection from the face of the sample as well. This free space technique has the advantage of being non-destructive, quick to carry out, and able to measure a wide range of frequencies in a single test (the frequency range is only restricted by the specifications of the horns and the VNA) [9]. Figure 8 shows results from the SMC material with different ratios of filler and glass fibre.

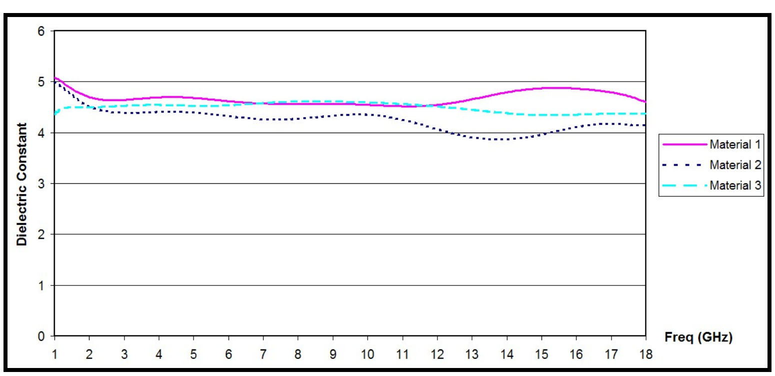

Figure 8 – Dielectric Constant vs. Frequency

6. Discussion

From Section 3 it is clear that material cure time is inversely proportional to the maximum temperature used in the curing profile. Further more, it is also evident that the size of the voids that form in the material is proportional to the maximum temperature used in the curing profile. Figures 2-4 show that material behaviour can be described as viscous in the early stage of curing profile until elastic behaviour dominates when the storage modulus, G', crosses the loss modulus G'' at the later stage of the curing profile. The duration where viscous behaviour dominates depends on the maximum curing temperature. Lower curing temperature results in longer duration of viscous behaviour and conversely higher curing temperature results in shorter duration of viscous behaviour. As a result, the curing profile can be optimized to minimize the shear stress imposed during the antenna embedding process.

The dielectric constant of the material appears to be suitable for use in encapsulation of microstrip antennas. For example, at 1.5GHz, the materials have dielectric constants of approximately 4.8, 4.7 and 4.5 respectively. Future work may include the use this material to create a microstrip line of known width which will permit us to verify that these values for dielectric constant are correct.

7. Conclusion

At low temperatures material behaviour is mostly controlled by the loss modulus G'' but at a higher temperature once the material has cured, the storage modulus G' takes over and is the dominant controlling factor. The free space technique was used to determine the dielectric constant of the materials, and they were found to be within the range suitable for use in the intended application. These preliminary results seem to indicate that from both the material processing and antenna performance point of view, there is a sound basis to embed antennas to cater for a wide range of frequencies in a polymeric composite material host such as Sheet Moulding Compound. There are however, direct implications on the planar configuration on the antenna to be embedded from measurements of the viscous force (as indicated by G' and G'' measurements) during the curing process. This process is expected to be optimized for the class of materials and antenna types used in this study as part of the on-going investigative work.

Acknowledgment

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