

Applications of Microwaves in Non-Destructive Testing

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ABSTRACT

This paper describes a new area of application of microwave energy in non-destructive testing (NDT), in which the quality of adhesively bonded products can be detected by the intrinsic spectrum signals generated by a variable frequency microwave (VFM) source. When microwave energy is launched into a metallic cavity, which is partially or fully loaded with a material, the electromagnetic energy reflects backward and forward between the cavity walls and travels through the material many times until a final standing wave condition is established. Materials property variables like internal or surface defects, dielectric properties, physical geometry and physical and chemical properties can contribute to its unique signal output characteristics. The reflected and input signals form a ratio, percentage of reflectance, which can be monitored and plotted as a function of the frequency. The percent of reflectance against frequency curve is called the microwave reflective spectrum. The spectrum generated can be used as a signature curve for assessing bond quality during processing. By this way, the same material under the same processing parameters provides a common characteristic curve, which can be used as a tool to provide a rapid, on-line, non-intrusive, non-destructive and volumetric monitoring of adhesively bonded polymer materials.

Keywords: variable frequency microwaves (vfm), reflective spectrum, microwave-assisted non-destructive evaluation and adhesives.

INTRODUCTION

Microwave irradiation is a unique energy source, which offers an alternative means to provide fast processing times for an array of advanced materials using either single or multi mode fixed frequency, or multimode variable frequency. The unique feature about microwaves is their deep penetration into materials with substantial reduction in process time, often by as much as 10 to 1^[1]. The material properties of greatest importance to microwave processing of a dielectric are the complex relative permittivity $\epsilon = \epsilon' - j\epsilon''$ and the loss tangent, $\tan \delta = \epsilon''/\epsilon'$ ^[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 imaginary part of the permittivity ϵ'' is called the dielectric loss. 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 ϵ' to enable adequate penetration, should be combined with high values of ϵ'' and $\tan \delta$, to convert microwave energy into thermal energy. Microwave heating is basically volumetric and provides an even temperature distribution throughout the material. It is based on the interaction of an electromagnetic field with both the adherend (polycarbonate) and the adhesive. The amount of power absorbed (P) by the adhesive greatly influences its curing time and resulting bond strength, and is dependent on both the permittivity and the loss tangent of the adhesive as follows:

$$P = \frac{1}{2} \epsilon_0 \epsilon' \tan \delta E^2 (Wm^{-3}) \quad (1)$$

where: ϵ_0 is the dielectric permittivity in free space;
 E is the electric field strength.

Note that the adherend will also absorb the microwave energy in the same behaviour as the adhesive. But in this case the adherend is polycarbonate which is a low loss material and hence its microwave absorption capability is neglected.

Microwave assisted non-destructive evaluation (MA-NDE) techniques have been used in many areas under different names, eg microwave thermography, microwave imaging technique and microwave sensors^[3,4,5,6]. All these methods share many common theories, principles and measurement tools. All MA-NDE systems can be divided into two groups: active and passive systems^[7]. In the active systems, microwaves are directed at the object and property information is extracted from the reflected energy. On the other hand, in the passive systems, microwave energy or noise

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emitted from the body is used to extract the property information, eg temperature. Microwave NDE techniques are gaining popularity due to the emergence of new and advanced materials, eg polymeric and ceramic matrix composites, which pose new challenges for NDE and require new methodologies.

This experimental task uses the lap joint of two samples in a microwave field for non-destructive evaluation (NDE). The variable frequency microwaves (VFM) are generated by high power helix travelling wave tubes (TWTs) [8]. Helix TWTs provide all possible bandwidth requirements for applications requiring modest power levels. The VFM facilities available at the Industrial Research Institute, Swinburne University of Technology are Microcure 2100 model 250 and Microcure VW 1500. They are shown in Figures 1 and 2 respectively. Microcure 2100 model 250, which has a maximum power, output of 250 W and operates within a frequency range of 6.5-18 GHz. Microcure VW 1500 operates within a frequency range of 2-8GHz and has a maximum power output of 125 W. The cavity dimension of Microcure VW1500 are 250 mm x 250 mm x 300 mm and the Microcure 2100 model 250 has a cavity size of 300 mm x 275 mm x 375 mm. A block diagram of the system of Microcure 2100 is shown in Figure 3.

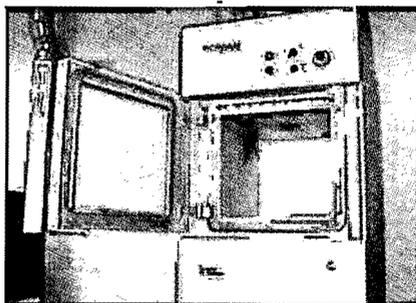


Figure 1: A VFM Facility, Microcure 2100 model 250.

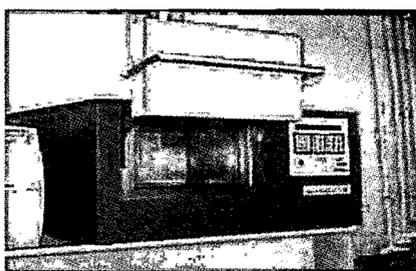


Figure 2: Another VFM Facility, Microcure VW 1500.

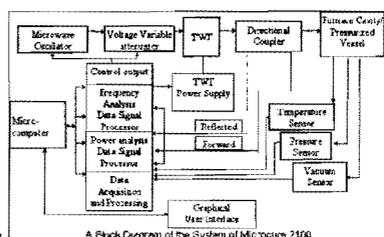


Figure 3: A Block Diagram of the System of Microcure 2100.

In order to test the suitability of an adhesive joint for a particular application, a representative sample joint (adherend and adhesive) was used for evaluation. The adherend, polycarbonate, has a low loss and much of the microwave energy is expected to interact to a great extent with the adhesive [9]. The result of such microwave energy penetration permit a fast curing and strong joining of the two sheets of polycarbonate.

PRINCIPLES OF THE RESONANT MODE MA-NDE

The resonant mode MA-NDE technique is based on the variable frequency microwave (VFM) concept and interactions between microwaves and materials at high frequencies. When a microwave signal of a given frequency is launched into a cavity which is fully or partially filled with material, the microwaves will reflect back and forth between cavity walls and travel through the material many times before establishing a final standing wave condition. There are three possible outcomes for the interactions of these waves:

- i. partially confined and partially reflected,
- ii. totally reflected back to the launcher, and
- iii. totally confined within the cavity.

The final condition depends on the cavity dimensions, frequency launched and material properties. The ratio between the reflected signal and the input signal can be monitored and plotted as a function of the frequency. This signal ratio versus frequency curve is called the microwave reflective spectrum.

Materials vary in dielectric property parameters over a wide frequency range, from high absorption with high penetration to extreme loss with a very small skin depth penetration. [10]. The dielectric properties of as-cured and post-cured samples show changes in high power microwave fields. The polymer chain motion can take place at temperatures far below the T_m , melting point. The polymer chain can vibrate and restrict crankshaft motions, if sufficient thermal energy is available [11]. A general trend appears in that there is an increase in dielectric parameters as the temperature rises. The test becomes reliable once the structure and quality bonding are identified through its impedance obtained from the bonded area. In general, the impedance is higher over the sound joint zone and lower over the disbonded area. One advantage of this characterisation testing method is the volumetric and rapid monitoring feature for which a couplant or a primer is not necessary. For a given frequency range and cavity dimensions, the dimensions and geometry of a material, the location of the material within the cavity, and the reflective spectrum are purely a function of the intrinsic properties of that material. Such spectrum generated can be used as a signature curve for assessing the product conformity during the curing processing. In other words, products of conforming quality will share a common characteristic curve, which is different from that of a lesser quality (non-conformity) products.

The study focused on the non-destructive testing method for adhesive bonding application of polycarbonate by microwave irradiation. Characterisation studies through utilisation of an appropriate frequency band for microwave processing of polycarbonate were performed. In a VFM environment, the microwave oscillator generated a signal, which was launched

into the multimode microwave cavity. A directional coupler identified the strength of the forward and reflected microwave signals. A controller compensated for the gain of the amplifier to ensure a constant forward power level across a range of frequencies, while sweeping occurred. The generated data was transmitted to an off-line PC which recorded the information including, frequency forward and reflected powers and also calculated a percentage of reflected energy to form the microwave reflective spectrum. This signal ratio output at a given frequency was used as an indication of all the interactions with materials inside the cavity.

EXPERIMENTS AND RESULTS

It was found that the best frequency to process the adhesive was in the frequency range of 9.5-12.5 GHz [1,9], which could also be conventionally cured at 65°C isothermally for 40 minutes. Microcure 2100 model 250 VFM facility was therefore employed for the experiment. The central frequency selected was 11 GHz with sweeping bandwidth of 1.1 GHz and sweeping rate of 0.1 second. The power output was 200 W. Polycarbonate samples of 101 mm x 25 mm x 1 mm were joined and the lapped area was 6.5 cm². After applying a calculated amount of the adhesive to the lapped area, the samples were then placed in the center of the cavity on top of a teflon block.

Microwave reflective spectra were then taken at the following moments during the cure status of the adhesive:

1. before cure with sample at 45°C for 6 minutes,
2. isothermally cured sample at 45°C for 10 minutes,
3. isothermally cured sample at 65°C for 6 minutes,
4. after sample isothermally cured for 20 minutes, and
5. after sample isothermally cured for 45 minutes.

All the spectra were taken in a frequency range from 10.8 GHz to 10.9 GHz as shown in Fig 4, with 20% offset in the y-axis between each spectrum.

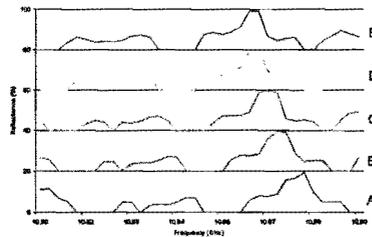


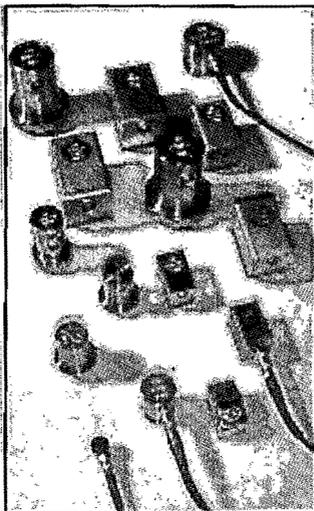
Figure 4: Microwave Reflective Spectra during Isothermal Adhesive Curing at 65°C.

In general, the spectra shift to the left during curing and the changes in peak location and shape are directly related to the change of the dielectric properties. Comparing spectrum A to B, the peaks not only shift to the left, but also change in shape and become flattened. Comparing spectrum B to C, the peaks become more flattened. Spectrum change between C and D is not much. Spectrum change between D and E is even less. In other words, the adhesive almost reached the ultimate extent of cure after isothermal curing at 65°C for 6 minutes by VFM irradiation and essentially no further reaction occurred after 20 minutes.

CONCLUSION

Microwave assisted nondestructive (MA-NDT) evaluation techniques using a resonant microwave mode was presented. Such an evaluation system provides an on-line, volumetric, non-contact, non-intrusive and non-destructive monitoring feature. By comparing a microwave reflective spectrum during the production processes to the standard spectra, a computerized monitored system can be used to regulate the process-input parameters for proper adjustment and compensation. Such methodology can be used for on-line assessing and real-time evaluating product quality. Successful application of this technique depends largely on the database gathered, which can greatly

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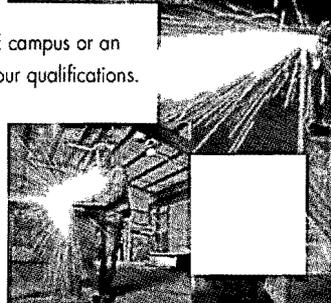
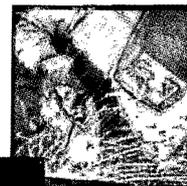
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Vol. 38 No.5 — September/October 2001

CONTENTS

**129 APPLICATIONS OF MICROWAVES IN
NON-DESTRUCTIVE TESTING**

**133 PART 8 — WELDING PROCESSES FOR
NON-DESTRUCTIVE TESTING PERSONNEL**
Peter Hayward

REGULAR ITEMS

117 EDITORIAL

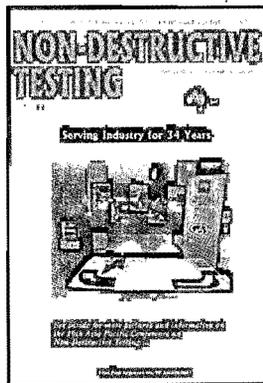
118 INSTITUTE NEWS

121 INDUSTRY NEWS

123 NEW PRODUCTS

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CONFERENCE ON NON-DESTRUCTIVE TESTING**



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