Relationship Between Microwave Irradiation & Constituents of Composites During Joining Process

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Two important things to be studied in the joining of thermoplastic composite materials using microwave irradiation are the relationship between the microwave energy and the matrix of the composite as well as that between the reinforcing fibre filaments and microwave irradiation. The characteristics of the thermoplastic matrix of the composite, eg structure, crystallinity, glass transition and heat-distortion temperatures are related to the heat transfer in the material during joining process. Microscopy study is used to find out the microstructural characteristics along and around the bondline of the welds. The separation distance of the reinforcing carbon filaments was varied and heat transfer in the material during joining was studied. The reasons why the thermoplastic matrix composite materials were weakened by prolonged microwave irradiation were also studied and analysed.

Keywords: *Variable Frequency Microwaves (VFM), Thermoplastic Matrix Composite Materials, Bondline, Keinforcing Filaments and Microwave Irradiation*

Introduction

The use of microwave energy in joining thermoplastic matrix composite materials has been well documented (Stokes, 1989; Varadan and Varadan, 1991; Siores, 1993; 1994; 1999; Liu et al; 1996; Ku et al, 1997a; 1997b; 1999b; 2000). This research starts with the concept of joining fibre reinforced thermoplastic (FRTP) matrix composite materials, eg thirty three percent by weight glass fibre reinforced low density polyethylene, LDPE/GF (33%), using microwave irradiation with and without primers. The joints, with araldite as primer, were then tensile shear tested and it was found that joints with araldite as a primer cured by microwave irradiation were stronger than those obtained by curing the primer at ambient conditions. This led to the idea that the araldite might have diffused into the thermoplastic matrix. In order to prove this, two surface analysis procedures were carried out. One was microscopy inspection and the other was x-ray photoelectron spectroscopy. Both analyses confirmed that diffusion had taken place (Ku et al, 1999b). This paper discusses the relationship between the constituents of thermoplastic composites with microwave energy during joining process. The first is the relationship between microwave energy and the structure of the matrices, the polymers. The other is the relationship between the reinforcing filaments, glass or carbon fibre filaments, and microwave energy.

Polymers and Their Structures

The basic unit of polymer is the molecule or, more accurately, the macromolecule, which is composed of thousand of atoms. The spine of these molecules is the carbon chain of atoms and there are three basic types of polymeric materials. These are linear, space network and elastomeric polymers (Flinn and Trojan, 1990; Morgan, and Gallagher, 1992) and are shown in Figure 1. The *linear structure* is a chain that is not a straight line but more like spaghetti (Flinn and Trojan, 1990). These molecules slide by each other upon heating and form the thermoplastic polymers. The *space network structure* is rigid and makes up the thermosetting polymers. The coiled structures exhibit elastic extension of as much as 1000% and are aptly termed elastomers. The molecular chains of a polymer may be completely tangled up or can be arranged in an orderly manner. If the chains are tangled up, the polymeric materials are said to be amorphous, otherwise they are crystallised (Flinn and Trojan, 1990). One of the thermoplastic matrix used in this research is LDPE which has a degree of crystallinity of 60% (Bolton, 1988) and therefore

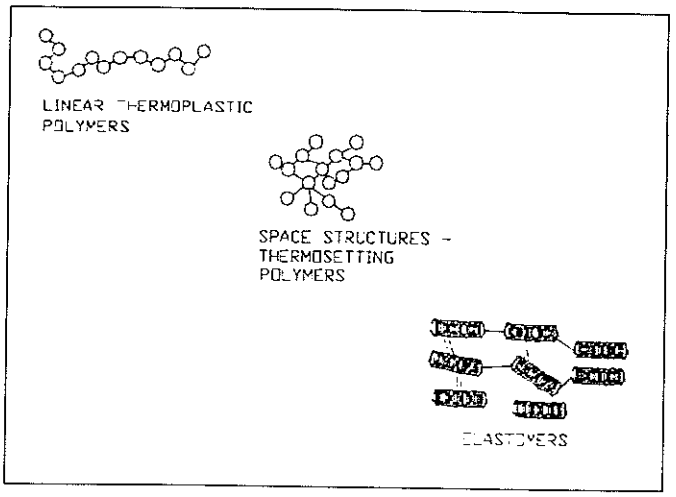


Figure 1 – Three Types of Basic Polymeric Materials

couples better with microwave energy than high density polyethylene, HDPE (NRC, 1994), which has a crystallinity of 100%.

Microwave Irradiation and the Matrix

In this research, thermoplastic materials, eg LDPE, polystyrene (PS) and nylon 66, are used as the matrices of the FRTP composites because they are generally flexible and relatively soft and if heated they become softer and more flexible. Their behaviour is totally due to their linear structure, in which the chain of each linear polymer slides over each other. In the joining of LDPE/GF (33%) using microwave energy with araldite as primer, it is expected that the araldite will absorb more microwave energy than the LDPE/GF (33%) and convert it into heat (Ku et al, 1999b). The heat will initially heat up the primer and the heated primer will then conduct the heat into the composite. The matrix of the composite is a thermoplastic resin, LDPE with linear structure and low glass transition temperature, T_g, -120°C. The percentage of free volume is therefore high (Flinn and Trojan, 1990) and the chains of each linear polymer slide over each other easily with the limited supply of conducted heat. This is proved by the microscopy study (Ku et al, 1999b).

Plate 5 – 1000 Times Magnification of Bondline with Joining Parameters of 2.45 GHz, 800 W and 80 seconds

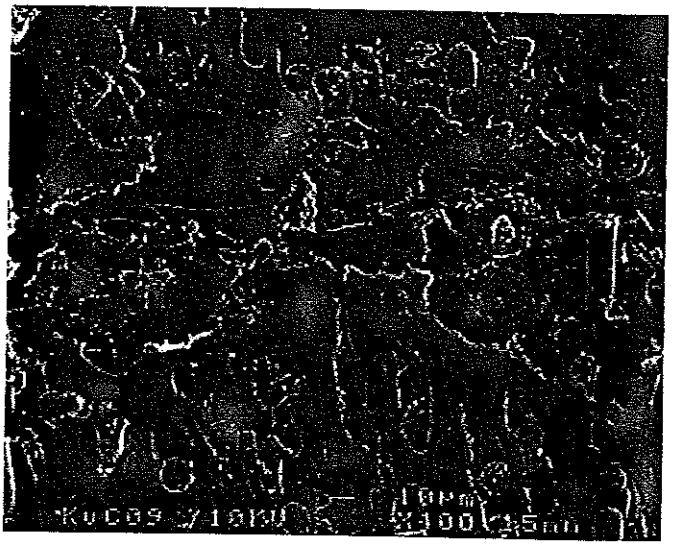


Plate 7 – 400 Times Magnification of Bondline with Joining Parameters of VFM, 200 W and 420 seconds

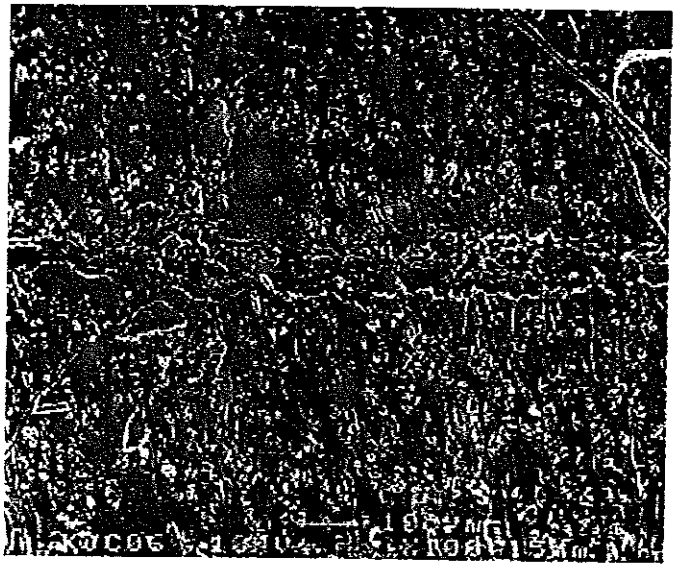


Plate 6 – 100 Times Magnification of Bondline with Joining Parameters of VFM, 200 W and 420 seconds

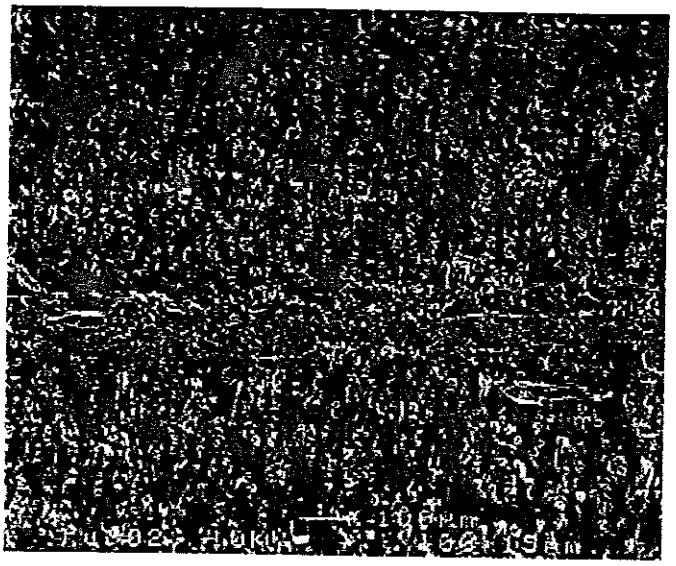


Plate 8 – 100 Times Magnification of Bondline with Joining Parameters of VFM, 200 W and 450 seconds

420 and 450 seconds. First, the sample with an exposure of 420 seconds to VFM irradiation was studied. At 100 times magnification, it was found that the bondline was observed to have black colour, while the parent material in the matrix was grey. This is shown in Plate 6. Only very few glass fibre filaments appeared on the bondline. At 400 times magnification, some glass fibre filaments were found as bright patches on the bondline as depicted in Plate 7. The microscopic observations found were similar to those found in Plates 1 and 2 respectively except that less glass fibre filaments on the bondline inferred that diffusion of the parent material to the araldite and vice-versa was not so obvious as in the fixed frequency case. Four hundred and twenty seconds are the maximum exposure time of the composite to VFM before the parent material is damaged (Ku et al, 2000a). Next, the sample with an exposure time of 450 seconds to VFM energy was investigated and it was at this time of exposure that the parent material was weakened (Ku et al, 2000a). At, 100 and 400 times of magnifications, similar microscopic characteristics were observed as in the case of an exposure time of 420 seconds and were shown in Plates 8 and 9 respectively. In both cases, no change of phase was inferred. However, since more glass fibre filaments were present in the bondline, it could be argued that they had been flushed due to flowing of the melting parent material, ie LDPE/GF (33%) into the araldite, primer.

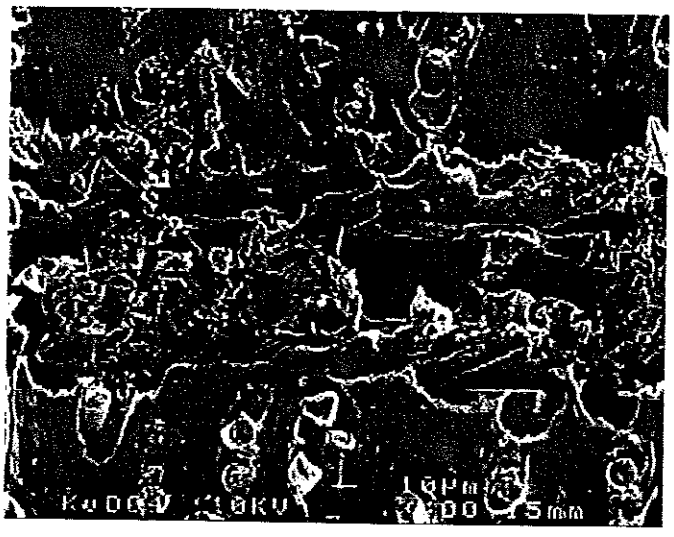


Plate 9 – 400 Times Magnification of Bondline with Joining Parameters of VFM, 200 W and 450 seconds

5 is fitted into the curves of Figures 6 and 7 respectively. Referring to Figure 7, it is found that there is only one peak for the intensity of carbon atoms, which represents carbon atoms in C-H and C-C bonds in LDPE/GF (33%). Referring to Figure 6, it is found that there are two peaks for the intensity of carbon atoms; one represents carbon atoms in C-H and C-C bonds in LDPE/GF (33%) and the other independent carbon atoms (graphite). This concluded that independent carbon atoms exist in the black patches.

Referring to Figure 3, the diameter of the carbon fibre is 0.5 mm and its length is 6 mm. Its volume = $\pi/4 \times (0.5)^2$ mm^3 = 1.178 mm^3 or 1.178 x 10^{-3} cm^3.

Since the density of the carbon fibre is 1.86 g/cm^3 (Matthews and Rawlings, 1994), the mass of the carbon fibre = volume x density

= 1.178 x 10 cm^{-3} x 1.86 g/cm^3 = 2.191 x 10^{-3} g.

The specific heat capacity of the carbon fibre is 0.61 J/gK (Borgnakka and Wylen, 1998) and the energy absorbed by the carbon fibre by bringing it from room temperature (25°C) to 115°C

= mass x specific heat x change in temperature

= 2.191 x 10^{-3} x 0.61 x (115-25) = 0.12 (J), which was the energy transferred to the thermoplastic matrix.

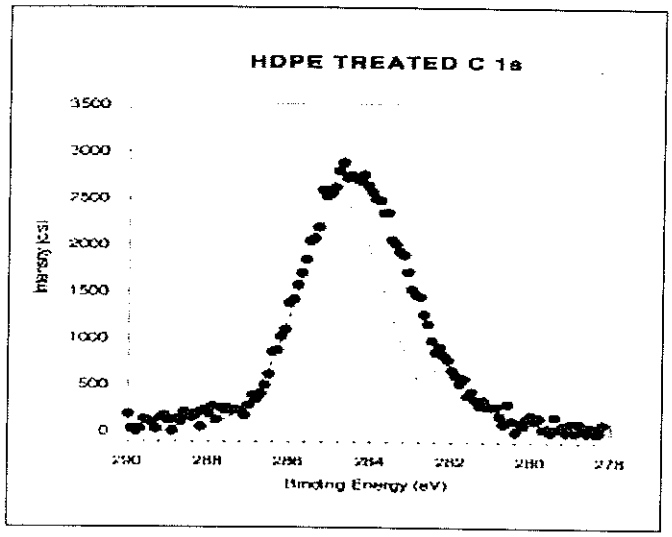


Figure 6 – The Two Peaks of Intensity for Carbon Atoms in the Sample with Black Patches

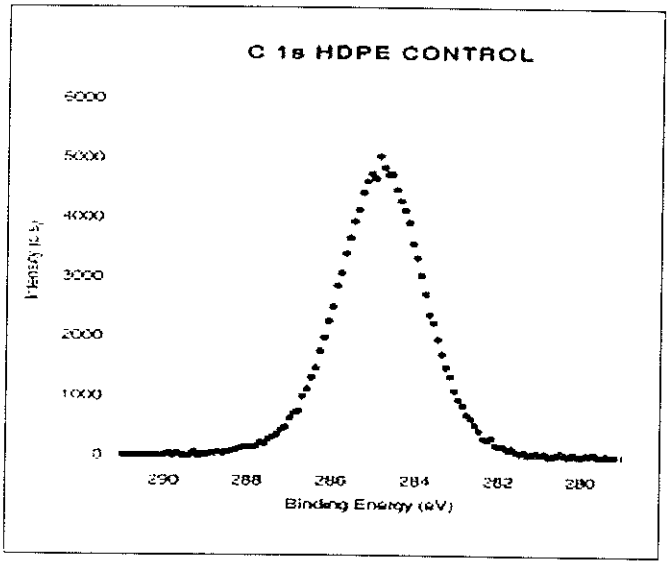


Figure 7 – The Peak of Intensity for Carbon Atoms in the Control Sample

Referring to Figure 3, the diameter of the patch is 0.5 mm and its depth is 0.005 mm. Its volume = $\pi/4 \times (0.5)^2 \times 0.005 = 0.982 \times 10^{-3}$ mm^3 = 0.982 x 10^{-6} cm^3.

Its mass = density x volume = 0.92 x 0.982 x $10^{-6} = 0.9 \times 10^{-6}$ g.

In a mer of LDPE, there are one C-C bond and 4 C-H bonds. The energy required to break one-gram mole of the C-C bond is 334.88 KJ and of the 4 C-H bond is 4 x 443.716 KJ (Flinn and Trojan, 1990).

The energy required to break the C-C bond (black patch) in Figure 3

$$= \frac{0.9 \times 10^{-6}}{28} \times 334.88\text{KJ} = 0.011\text{J}.$$

Similarly, the energy required to break the C-H bond (black patch)

$$= 4\text{x} \frac{0.9 \times 10^{-6}}{28} \times 443.716\text{KJ} = 0.057\text{J}.$$

Total energy required to break all the bonds of the LDPE (charred area)

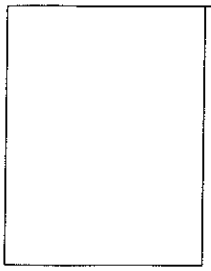
= 0.011 J + 0.57 J = 0.068 J.

The energy transferred from the carbon fibre to the matrix of the composite was found to be 0.12 J which was enough to break the bonds of the LDPE and char it.

In joining LDPE/CF (33%) with a fixed frequency of 2.45 GHz and at the power level of 400W, it was found that the material started to arc after being exposed to microwave irradiation for 8 seconds (Liu, 1998). Again, in joining PS/CF (33%) with a fixed frequency of 2.45 GHz and at the power level of 400 W, the composite started to arc after being exposed to microwave energy for 11 seconds (Lee, 1999). In short, the composite materials started to arc in less than 11 seconds when exposed to the power of 400 W. Comparing these results with those of the independent carbon fibre filaments' study in this research, it was found that the composite materials coupled better with microwave irradiation. The reason behind this is that the filament-to-filament distance in the FRTP composites is much less than 1. The filaments, once heated, conducted heat in their respective neighbourhood easily and in addition, in the closely packed FRTP composites (33% by weight of fibre filaments), some of the filaments may have touched one another which may have led to d.c. conduction, both of which will heat the composites up and cause arcing at a much lower power level and time of exposure. On account of the above reasons and when the strength of the composite can be compromised, it can be argued that the amount of carbon fibre filaments in the composites can be reduced to cut the cost of the materials, which at the same time can couple with microwave irradiation more efficiently.

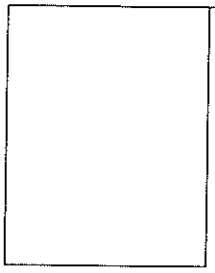
The last topic to be discussed concerns about the weakened parent materials observed, in which two of the five FRTP composite materials studied, PS/CF (33%) and LDPE/CF (33%), were weakened by excessive exposure to VFM irradiation. The discussion is split into two parts; one part deals with the effect of VFM energy on the reinforcement of the composite, ie the carbon filaments, while the other is concerned with that in the matrix of the composite, ie the thermoplastic.

Considering the joining of PS/CF (33%) using VFM with no primer the power used was 100 W, the maximum exposure time was 120 seconds and the maximum temperature reached was 95°C, which was higher than the heat-distortion temperature (82°C) of PS (Flinn and Trojan, 1990) and the temperature limit in air for carbon filaments impregnated in polyethylene or polystyrene (93°C) (Budinski, 1989). The matrix and the reinforcement of the composite were damaged. The bonds of the matrix, PS, were broken, leaving behind black carbon as mentioned in the previous paragraphs. The tensile strength values obtained for PS/CF (33%) were lower than those procured for PS/GF (33%) by around 100 N (Ku et al, 2000a) and this provided an extra proof that the carbon fibre filaments were damaged by prolonged VFM irradiation because the carbon fibre filament (3100 MP_a) is stronger than the glass fibre filament (2200 MP_a) (Matthews, and Rawlings, 1994). During the joining process, the carbon fibre filament coupled very well with microwave energy and was heated directly which cause damage to occur. On the other hand, the glass fibre



Elias Siores

Professor Elias Siores is the Chair in mechanical engineering and the Executive Director, Industrial Research Institute, Swinburne, Swinburne University of Technology, Australia. His current research is concentrated on advancing the science and technology in the field of Advanced Manufacturing Technologies. He has more than over 200 publications including 72 Journal Articles, 5 Book Chapters, 27 Invited, 44 Conference Refereed, 46 Conference Unrefereed and 10 Keynote Addresses. He worked for University of Wollongong and Queensland University of Technology, Australia as lecturer and senior lecturer before taking up Swinburne's Chair.



Jim Ball

Associate Professor, Jim Ball was born in Guildford, UK. He received the BSc degree in engineering from Leicester University, UK in 1964, the MSc degree in physics from the University of London, UK in 1968, and the PhD degree in electrical engineering from the University of Queensland, Australia in 1988. He worked as a microwave engineer for 7 years in UK and Australia. In 1971, he joined the University of Southern Queensland, where he is now the Head of Electrical, Electronic and Computer Engineering. His research interests are in the areas of microwave components, devices and measurements.