Carbon Nanotube Technology as an Option for Future Computing Devices

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Abstract. Carbon nanotubes (CNTs) offer the potential for radical transformation of future electronics as they exhibit conductivity, semiconductor and mechanical properties that far exceed those of traditional materials. They thus offer wide opportunities for novel computing devices, especially those required to be small and light, such as "wearables". They also offer environmental advantages by reducing energy demand in manufacture and use. A practical investigation is reported, focusing on microwave processing of a CNT composite sample. A significant reduction in energy consumption in manufacture while increasing mechanical and electrical performance is deduced, suitable for low power wearable, wireless computing devices. However, CNTs inherently suffer from flaws such as the tendency for nanoparticle agglomerations to form due to strong covalent bonds, and other uncertainties in nanoparticle behaviour. This experimental study demonstrates that microwave processing of CNT composites can reduce the power consumption and the temperature generated during the manufacturing process.

Keywords: Future computing devices · Wearable devices · Carbon nanotubes
Epoxy nanocomposites · Microwave curing

1 Introduction

The discovery of carbon nanotubes (CNTs) can be traced back to 1951 [1], although this was not widely publicised and their interesting properties were not discovered until much later. In 1992, a paper on their potentially very useful electrical properties was published [2], and subsequently the work on them has expanded in the 21st century, in parallel with the related work on graphene. The nanotubes, which are formed of tubes of graphene, have the potential to be very highly conducting, rivalling superconductivity or, in some circumstances, to have semiconducting properties. In addition, they have mechanical properties that are greatly in advance of traditional materials, as is also

the case with graphene and carbon fibres more generally. They thus have great potential for transformation of many aspects of the electronics and computing industries.

Already, a basic CNT computer has been constructed [3] and, even though it will take some time for this to overtake the advantages of silicon, the much-publicised limitations that silicon is approaching mean that searches for alternative materials are actively in progress: CNTs are strong candidates in this competition.

CNTs also offer great potential in the construction of hardware [13–16]. Their great strength means that thinner and lighter structures can be developed, and this is particularly relevant to the development of wearable technologies because less material is involved than is the case with metal or traditional plastics, there is less environmental demand on the sources of materials and, further, the environmental stresses in the manufacturing process are greatly lessened compared with metal (at least) due to the much lower processing temperature, as well as the likely reduced volume.

Furthermore, significant achievements include 1 GHz operation of CNT interconnects with silicon transistors [17], organic interconnects and spintronic switches [18], Cu-CNT composite interconnects as potential replacements of global Cu interconnects [19, 20], demonstration of Cu-like resistivity [21, 22] and integration scheme for CNT based Through-Silicon-Vias (TSVs) [23] as key enablers of 3D integration, etched in the silicon substrate.

For all these reasons it was considered timely to investigate carbon nanotubes in a laboratory specialising in carbon composite technology and hence some sample test pieces were created. The manufacture and processing of these were investigated and refined and some of the properties investigated. So far this has focused on mechanical properties, but electrical properties have also been studied via the context of the bulk microwave conductivity, this being immediately relevant to the processing of the nanotubes within an epoxy bonding matrix. This gives some indication of the future potential of the material in electronic applications, for which the project reported here is an initial stepping stone.

2   Experimental Work

2.1   Material

The epoxy resin system used in this study was Araldite LY 5052/Aradur 5052. Araldite LY 5052 is a low viscosity multifunctional epoxy system supplied by Huntsman, USA. Epoxy resin was produced from a reaction of bisphenol A resin and epichlorohydrin [4]. The hardener for this system was Aradur 5052 which is mixture of polyamines. Commercially available highly purified multi-walled CNTs (MWNTs) supplied by Electrovac, Austria (95% as per thermogravimetric analysis, having traces of metal and metal oxide) were added, having a density of 0.98 g/cm^3 (as per He pycnometery), specific surface area of 26 m^2/g, average length up to 2500 nm and average diameter of 50 nm. The synthesis method used was Chemical Vapour Deposition (CVD). The mix ratio of epoxy resin to hardener was 100:33 parts by weight which corresponds to 24.8% of hardener and 75.2% of resin, according to amine/epoxy ratio, due to high chemical activity of amine groups [5].

2.2 Specimen Preparation

The components of resin and hardener were weighed accurately according to the processing data and hand mixed. Pre-calculated amounts of CNTs and epoxy resin were carefully weighed and manually mixed together. MWNTs in the amount of 0.01 wt.%, 0.1 wt.% and 0.2 wt.% were infused in the matrix and dispersed via bath sonication (Ultra 7000, ultrasonic frequency: 42 kHz, power consumption: 50 W) for 1 h. Afterwards each epoxy system was divided into 6 parts and poured into glass tubes. The tubes were put into a vacuum oven for 1 h to remove the presence of air before microwave curing.

2.3 Curing Procedure

The microwave setup used in this study was MARS 6 supplied by CEM Corporation, USA (magnetron frequency 2.45 GHz, power output 1800 W). It was used with vessels having self-regulating control of the temperature and pressure. MARS 6 automatically recognises the type and number of vessels that have been loaded, and adjusts the output power and other parameters. Neat epoxy resin (Epoxy 1) and an epoxy system infused with 0.01 wt.% CNTs (Epoxy 2), with 0.1 wt.% CNTs (Epoxy 3), and 0.2 wt.% CNTs (Epoxy 4) were cured under the same microwave conditions. The initial parameters used were: ramp time: 10 min, hold time: 1 min, temperature: 40 °C and maximum power: 500 W.

Fig. 1. MARS 6 microwave apparatus

2.4 Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) is a useful tool to determine post-curing processes as well as temperature transitions (melting, crystallisation and glass transition temperatures) in materials. DSC of all specimens was carried out using Perkin Elmer

Pyris 1 apparatus. The samples were cut into small pieces weighing from 5 mg to 10 mg using an engineering blade machine Labotom-3 supplied by Struers, Australia. Specimens were placed in aluminium plates containing a crimped lid with a small hole. The hole is necessary to maintain the constant pressure in the system and prevent deformation or rupture of aluminium pans. The DSC measurements were carried out from 30 °C to 250 °C at a high heating rate of 10 °C/min for three cycles under a nitrogen atmosphere. DSC was performed for the neat epoxy and all nanocomposite systems under the same conditions.

2.5   Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) in one of the most widely used methods for inspecting topographies of CNT nanocomposites and CNT distributions. SEM of all specimens was carried out using a field emission MIRA 3 TESCAN apparatus. The samples were cut into small pieces to fit into the machine using the engineering blade cutting machine Labotom-3. A conductive platinum sputter coating was used to coat samples prior to the testing. All SEM images were taken at 5 kV voltage.

3   Results and Discussion

Figure 2 shows the power profile as a function of time applied by the microwave curing process in order to maintain the set minimum temperature of 40 °C. The power profile has the same characteristics for the epoxy and nanocomposite samples during the curing process. Three stages in Fig. 2 can be noted. Stage 1 (up to 12 s) of the graph shows a sharp decrease in the power as the sample heats up. As shown in Fig. 2, during this stage the power decreased rapidly as the default initial power (500 W) was relatively high. The fall of the curve extends until the consumed power reaches approximately 110–120 W. Afterwards, the epoxy and nanocomposite systems start to react and generate heat within the sample. As can be seen from Fig. 1, the chemical reaction occurred over a small period of time, from 12 s to 154 s, which may be referred as stage 2. The epoxy-amine reaction is the dominant reaction during the microwave curing process [6, 7], whereas the epoxy-hydroxyl groups are more dominant during conventional heating. The reaction can only take place from a certain minimum energy called the energy threshold of the reaction [7]. In this study, it can be considered that the energy threshold occurs at 12 s, after which an active chemical reaction of the curing process started. During stage 2, the microwave energy is absorbed by the epoxy system and maximum power consumption was found to be around 220 W. At the third stage of curing (after 154 s), in all cases, no energy consumption was observed (Fig. 2). The epoxy resin system ceased to consume microwave power and no further external energy was required for curing.

The area under the power-time curve was calculated by integration (Eq. 1), where a and b limits are 0 and 160 s. Theoretically, it defines the amount of potential energy absorbed during the microwave processing. The obtained values are presented in Table 1: this indicates the amount of energy consumed for curing neat epoxy and nanocomposites. It was found that with the smaller addition of CNTs, more energy was required for
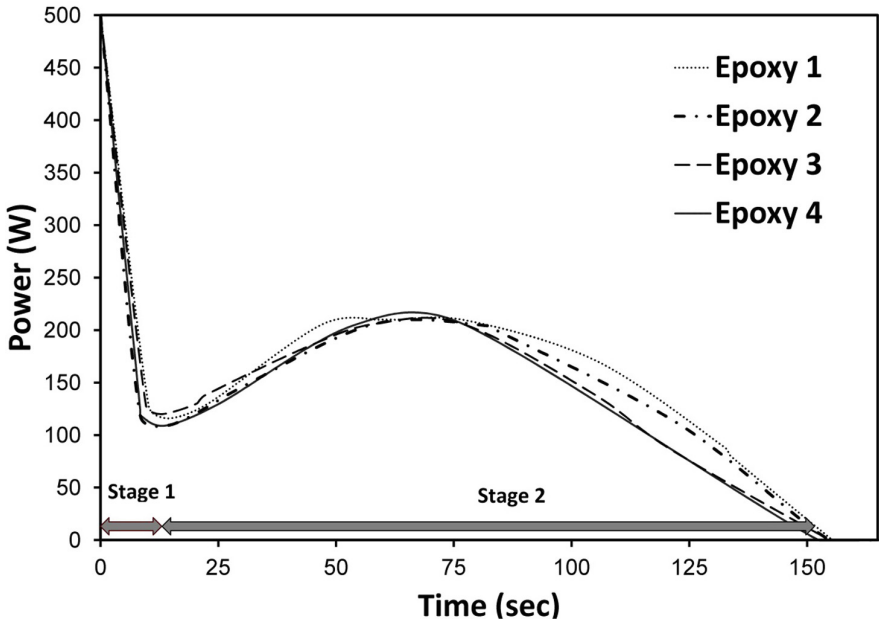
Fig. 2. Power profile for the samples obtained using microwave curing

microwave curing. The areas under the curves were evaluated and compared. The experiments allowed a 12.5% energy reduction by employment of 0.2 wt.% of CNTs in the epoxy matrix (Table 1). Therefore, it can be concluded that CNTs can significantly lower the microwave energy consumption for curing epoxy nanocomposites.

$$Area = \int_{a}^{b} f(x)dx \tag{1}$$

A series of DSC tests were conducted in order to observe the degree of cure for epoxy and nanocomposite samples. DSC analysis confirmed that all microwaved epoxy and nanocomposites were completely cured since there was no evidence of chemical reaction during testing (post-curing process). If the system is fully cured, the absorption of heat will not occur and the epoxy system can be re-heated and re-cooled reversibly below its glass transition temperature Tg [8]. A cyclic execution of this test is an accurate way for analysing the degree of cure compared to a single heating cycle. In this work, three heating/cooling cycles were conducted prior to the reporting of results (Table 1). All microwaved samples were fully cured significantly before the curing time specified by the supplier of the epoxy system [9]. The technical data sheet recommends curing (at room temperature) and post curing (at 100 °C) times of at least 4 h 40 min.

The temperature of the microwave process could not be controlled or changed manually during the curing because the microwave oven is programmed to be self-controllable. The temperature-time profile of the microwave heating of epoxy and nanocomposite systems is presented in Fig. 3. In contrast to the power-time curves (Fig. 2), the temperature profile was divided into two stages of the process. Stage A (up to 325 s) shows a gradual increase of temperature of the microwave curing process. By analysing this stage, it was possible to observe gradual heat release from the chemical reaction. This was attributed to the dipole moments and their polarisation in the electromagnetic field [10–12]. Stage B shows gradual reduction of curing temperature due to the process of crosslinking and the progressive curing of the composites. By the end of this stage, the material was fully cured and hardened. As can be implied from the power-time graphs (Fig. 2), consumption of power took place during stage 2 of the curing (until 154 s), and Fig. 3 shows temperature rising at the same time. Based on these results (Figs. 2 and 3), it can be concluded that after 154 s of the heating process, heat was generated from inside the system during exothermic reaction and no external heating was needed for curing.

At higher temperatures, above 50 °C, it was found that the monolithic Epoxy 1 (Fig. 3) required a higher amount of heat as compared to any other system. Monolithic Epoxy 1 had the highest curing temperature of 73 °C as compared to 58 °C for the Epoxy 4 (0.2 wt.% CNTs) system. Here, a reduction of 20.5% in temperature can be seen because of the addition of 0.2 wt.% CNTs. Moreover, the higher content of CNTs lowered the temperature required for full curing of epoxy nanocomposites (Fig. 3). This may be attributed to the high electrical and thermal properties and selective heating of CNTs which allow the production of materials at lower temperatures. CNTs create conducting paths and absorb microwaves efficiently and this may lead to rapid curing: it also indicates the potential for CNTs in advanced electronics. The microwave energy was applied directly to the material and as a result, no further side reactions or
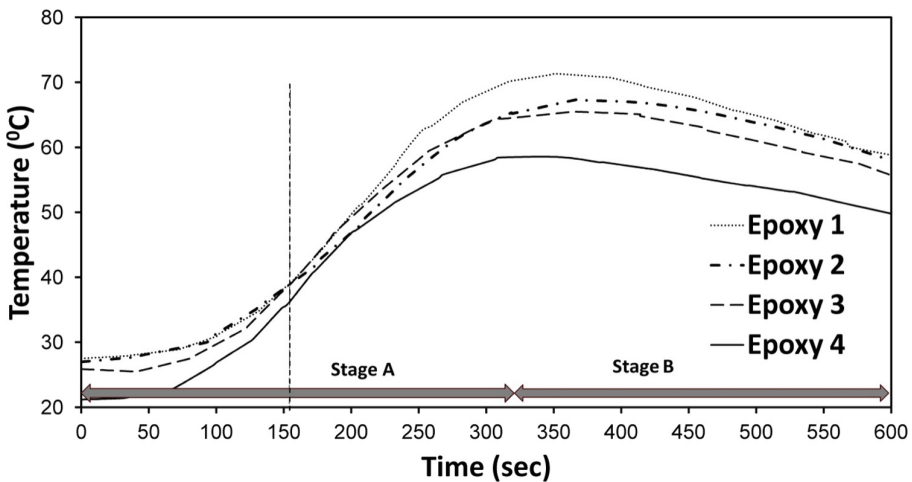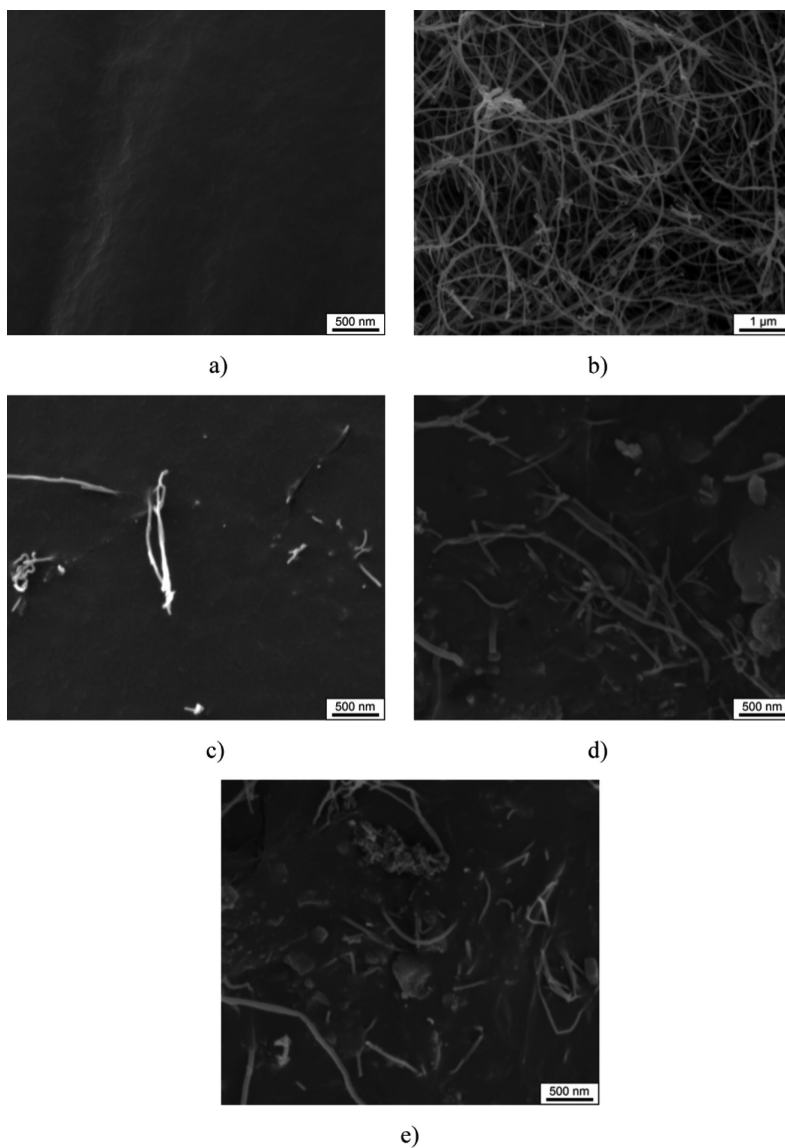

Fig. 3. Temperature profile for epoxy and nanocomposite samples. The dotted line shows the point where the energy consumption was 0 W

Table 1. Summary table for microwave cured samples

Epoxy	wt.% of CNTs	Energy, J	Maximum temperature reached during curing, °C
Epoxy 1		416	71.3
Epoxy 2	0.01	390	67.4
Epoxy 3	0.1	380	65.5
Epoxy 4	0.2	365	58.5

Fig. 4. SEM images of studied materials: (a) Epoxy 1; (b) CNTs; (c) Epoxy 2, (d) Epoxy 3 and (e) Epoxy 4

heat losses were observed. These observations are very important from a manufacturing perspective because they indicate significant energy and time savings.

Figure 4 depicts a series of SEM images obtained for CNTs, neat epoxy resin (Epoxy 1) and CNT composites (Epoxy 2–4). CNT agglomerates can be clearly seen as well as individually dispersed CNTs (Fig. 4, c–e). This may be attributed to an inefficient sonication process via bath sonication, as described earlier. The ultrasonic technique was not strong enough to break covalent bonds and fully eliminate CNT clusters: this is the main obstacle in creating advanced CNT composites: a tendency of nanoparticle agglomerations to form due to strong covalent bonds. These agglomerations indicate an uneven volumetric CNT dispersion and could lead to unbalanced distribution of properties in greater material volumes. However, it can be observed that the individual CNTs are not broken after 1 h sonication and therefore should retain their original structures and properties.

Despite the agglomeration effects, the SEM images demonstrate that CNT networks have a great potential to create a 3D conductive platform via an efficient sonication process (Fig. 4). Further investigations into an improvement of the sonicating process are in progress.

4   Conclusions

Experiments to refine manufacturing procedures for carbon nanotube composite materials have been reported. Specifically, the effect of CNT addition on the microwave curing of epoxy resin composites was investigated. CNT filled epoxy nanocomposites can be manufactured in a few minutes with significantly reduced energy consumption compared to a monolithic epoxy resin without CNTs. The experiments conducted showed reductions of 12.5% in energy and 20.5% in temperature by adding 0.2 wt.% of CNTs to an epoxy matrix. Differential Scanning Calorimetry analysis confirmed that microwaved CNT-filled epoxy nanocomposites were completely cured. This may be attributed to the good electrical and thermal conductivity and microwave absorbing properties of CNTs. However, SEM images showed varying degrees of unevenness in the distribution of CNTs in the samples, indicating a need for further investigations into the sonication processing: these are being conducted. However, the enhanced conductivity shown by the microwave properties gives confidence that CNT-based materials are close to being ready to be implemented in electronic and computing devices and are already an advantageous choice for the mechanical parts. Being lightweight, the mechanical parts would be especially suitable for wearable wireless devices, which have a great potential for many applications. Further, CNTs in the electronic parts offer the possibility of greatly reduced power consumption, hence reducing battery drain, which is a major problem for wearable devices.

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