CHAPTER 7

Microwave Absorbing Behavior of Glass Fiber Reinforced MWCNT-PANi/Epoxy Composite Laminates

7.1 Introduction

Hybrid composite systems are composite materials formed by reinforcing two or more materials of varying properties. They are strong candidates for making structural components in many fields such as in transportation, aeronautics, naval, automotive and aerospace industries and as components for the electronic industry. Polymer matrix reinforced with glass or carbon fibres have been widely used as structurally strong composite materials. Epoxy or polyepoxide is a thermosetting epoxide polymer that cures (polymerizes and cross-links) when mixed with a curing agent or "hardener". Epoxy resins are well established as thermosetting matrices for advanced structural composites, displaying a series of promising characteristics for a wide range of applications owing to their excellent mechanical properties, low cost, ease of processing, good adhesion to many substrates, and good chemical resistance. The mechanical properties can be highly enhanced by the addition of glass fibers to the epoxy matrix. Glass fiber reinforced polymer (GFRP) composites are increasingly used in many structural applications replacing metallic materials due to their low cost, high strength and high chemical resistance. In most of these GFRP applications, the fibers play a major role in tensile load carrying capacity of a composite structure as the matrix is the weakest part in the composite. Epoxy resins are electrical insulators and, consequently are transparent to electromagnetic waves. Structurally strong conducting composite materials are commonly made either by incorporating conducting fillers into an insulating matrix or by applying a conductive coating over the insulating surface of the composite. Therefore, structurally strong and electrically conducting composite systems can be used for conducting as well as structural applications such as in radar absorbing (stealth), antistatic, corrosion protection materials etc.

The effectiveness of the absorber made by incorporating conducting fillers in the polymer matrix depends on the type of the filler and the degree of its dispersion in the composite. Ferrites and iron-carbonyl particles are most often used as magnetic fillers in microwave absorbers. However,
they have some drawbacks such as heavy weight, sensitivity to corrosion, poor processability, high cost and utility over a narrow bandwidth. Carbon nanotubes have received considerable scientific interest due to their low specific mass and excellent electrical, thermal and mechanical properties. The addition of high aspect ratio CNTs or CNT composites (SWNTs and MWNTs) at low loading levels in polymer matrices tend to yield composite materials with superior properties. Also, the EMI shielding and EM absorbing ability of MWCNT/PANi nanocomposites have been investigated by several researchers [4, 7, 8] and has been explained in the sections “5.3.4 EMI shielding and microwave absorption analysis, 6.3.6. EMI shielding and microwave absorption analyses”. In addition, the mechanical properties of either PANi or MWCNT/PANi composites are very poor and hence it is necessary to incorporate these materials into a suitable matrix. The dispersion of PANi-based fillers in an insulating polymer changes the dielectric constant of the latter and produces a composite with a very high capacity to absorb or reflect electromagnetic radiation [319]. The EMI shielding and microwave absorbing abilities of MWCNT/PANi filled poly(methyl methacrylate) composite was investigated by Makeiff et al. [9]. Similar studies on MWCNT/PANi -poly(styrene) composites has been carried out by Saini et al. [5] and these results support the utility of MWCNT/PANi as a conducting filler in thermoset or thermoplastic polymers. The electrical conductivity and the complex permittivity are the two critical parameters which decide the absorptivity of a material [320]. The introduction of MWCNT/PANi filler in the epoxy matrix can improve the conducting, dielectric and mechanical properties of the composites.

In the present study, MWCNT/PANi composites were prepared by in situ polymerization of aniline with varying the amounts of MWCNT (0.5–12 wt%). The MWCNT/PANi (with 8 wt% of MWCNT) composite with good electrical conductivity was added as filler to the epoxy matrix and stirred well using a mechanical stirrer. The MWCNT/PANi modified matrix was used to prepare the GFRP laminates by wet-layup vacuum bagging method. The amount of the filler (MWCNT/PANi) in the epoxy matrix was varied from 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 wt% with respect to the epoxy-hardener system, where as the fiber amount was kept constant in all the laminates. The hybrid laminates were then characterized and microwave absorption analysis was carried out. The MWCNT/PANi composites optimized for the electrical conductivity (Chapter 5) could not be used to fill the epoxy resin-hardener system ((LY556 and HY951) due to the poor solubility of the composite in either of the two components of the matrix. MWCNT/PANi
prepared using HCl as the dopant acid showed the better dispersibility in the epoxy matrix. Also, the electrical conductivity of the MWCNT/PANi composites made using HCl is of the same order of magnitude, as compared to MWCNT/PANi prepared using MSA as the dopant. Therefore, different MWCNT/PANi composites were made with varying MWCNT wt% in PANi using the optimized experimental conditions explained in the section “5.2.2 Preparation of polyaniline carbon nanotubes composites by in situ chemical oxidative polymerization”

7.2 Experimental

7.2.1 Materials required
Aniline, ammonium persulphate (NH4)2S2O8 (APS), hydrochloric acid (HCl), were procured from Merck (analytical grade), MWCNT were received from Yunnan Great China. Aniline was distilled under reduced pressure and stored below 4°C. All other reagents were used as received. Epoxy resin (Araldite LY556) and the hardener (HY951) were procured from Devi Chemicals, Coimbatore. Bidirectional glass fibre with a density of 2.5gm/cc was used for the laminate preparation.

7.2.2 Preparation of polyaniline-carbon nanotube nanocomposite by in situ polymerization
MWCNT/PANi composite was synthesized by an in situ chemical oxidative method, which has described in the section 6.2.2.2. Different nanocomposites were prepared by adding 0–12 wt% of MWCNTs during the polymerisation of aniline.

7.2.3 Preparation of laminates by hand lay-up vacuum bagging method
Vacuum bagging uses atmospheric pressure as a clamp to hold the laminate together. The laminate is sealed within an airtight envelope and when the bag is sealed to the mold, pressure on the outside and inside of this envelope is equal to atmospheric pressure. As a vacuum pump evacuates air from the inside of the envelope, air pressure inside of the envelope is reduced while air pressure outside of the envelope remains same. The pressure differential between the inside and outside of the envelope determines the amount of clamping force on the laminate. Figure 7-1 shows a schematic of the vacuum bagging method. Epoxy polymer resins are extensively used in the aerospace industries because of their superior properties and hence the same was used for the laminate preparation. EMI shielding and microwave absorption analyses were carried out using two ports Rohde and Schwartz ZVB20 Vector Network Analyzer. Microwave measurement was made in the S band frequency of ISM band (2–4GHz) with the laminates in the dimensions (a x
b) 40mm x 80mm. Sample was kept between two coaxial to wave guide adapters and tightened and then connected to network analyzer after the calibration without the test sample.

Figure 7-1: The components present in the vacuum bagging method. Source: Vacuum Bagging Techniques

A stoichiometric mixture of 11g of HY951 for 100g of LY556 was used for the laminate preparation. The reinforcement used was bidirectional glass fabric with a fiber weight of 310gsm. Hand lay-up vacuum bagging method was used for preparing the laminates and the fiber weight fraction was 70±2 % in all laminates. The resin was modified by the addition of conducting MWCNT/PANi (with 8wt% of MWCNT in it) and followed by mechanical stirring for 10 minutes at 4000rpm. Calculated amount hardener was added to the MWCNT/PANi modified epoxy resin at room temperature and stirred well to have a homogeneous mixture. The amount of MWCNT/PANi was varied from 0.5 to 3 wt% in the resin and beyond that, it found difficult to homogenize the solution. The modified resins were impregnated by hand into fibres which are in the form sheet or bonded fabrics. This was accomplished by rotating rollers in a bath of MWCNT/PANi modified resin. The procedure was continued for five glass fiber layers and the wet laid-up laminate was sealed using a plastic film. Using a vacuum pump, air under the bag is extracted and allowed to cure at room temperature for 24h. A laminate with unmodified (neat) epoxy was also prepared with the same fiber weight for the comparison purpose. Various stages in the laminate preparation are in the Figure 7-2. The schematic for the preparation of glass fiber reinforced MWCNT/PANi-epoxy composites and the samples of the prepared laminates are shown in Figure 7-3
7.2.4 Characterization

The surface morphological analysis of MWCNT/PANi composite and the laminate were done using a High Resolution Transmission Electron Microscope (JEOL JEM 2100- HRTEM) and by
a field emission scanning electron microscope (FE-SEM, Hitachi S4800). The room temperature electrical conductivity of the pressed pellets of MWCNT/PANi composites were measured using a four-point probe with a D.C. and A.C. current source (Model 6221) and a nanovoltmeter (Model 2182A) from Keithley instruments. DC conductivity of the laminates was measured using a Keithley source meter (Model 2635A). Tensile properties of the laminates were measured with a INSTRON 4204 mechanical tester at room temperature. The dynamic mechanical properties of the laminates were analysed using a Mettler DMA 861 analyzer. Experiments were performed at frequencies 0.2, 0.5, 1, 2, 5 Hz. The EMI shielding and microwave absorption analyses were carried out using two ports Rohde and Schwartz ZVB20 Vector Network Analyzer in the S band frequency of ISM band (2–4GHz). The samples (dimension of (a x b) 40mm x 80mm) were kept between two coaxial to wave guide adapters and tightened and then connected to network analyzer after the calibration without the test sample.

7.3 Results and Discussions

7.3.1 Morphology analysis

Figure 7-4 (a) and (b) show the TEM images of MWCNT and MWCNT/PANi composite used for the laminate preparation. The TEM images confirmed the presence of PANi surface coating on MWCNTs. Formation of PANi-coated MWCNT morphology facilitates the π–π* interaction between the surface of MWCNT and the quinoid rings of PANi and the extent of interaction alters the electrical conductivity of the composite. The mechanism of the formation of PANi coated MWCNT has been described in the section “6.3.1.1 Morphological analysis.” Figure 7-4 (c & d) shows the SEM of the fractured surface of the laminate prepared with 3wt% MWCNT/PANi filler. SEM images clearly show the presence of glass fibers and polymer matrix present in the laminate. TEM of epoxy modified with MWCNT/PANi (Figure 7-4(e & f)) clearly shows the presence of MWCNT inside the polymer matrix. Zdenko et al. have demonstrated the possible interactions between epoxy and MWCNT/PANi nanocomposites. The free amino functional groups of PANi can form covalent bonds with epoxy groups of DGEBA in the epoxy matrix. The PANi is also physically bonded to the CNT surface. This can lead to strong interaction between the polymer matrix and the PANi-coated nanotube along the whole surface of the nanotube [322], leading to enhanced electrical and mechanical properties of the polymer matrix.
Figure 7-4: TEM images of MWCNT (a); MWCNT/PANi (b); SEM images (c & d) and TEM (e & f) images of glass fiber-reinforced MWCNT/PANI-epoxy laminate with 3wt% MWCNT/PANI.
7.3.2 Electrical conductivity
The DC electrical conductivity of MWCNT/PANi nanocomposites with varying loading of MWCNT, was measured using a standard four-point probe technique. Figure 7-5(a) shows the electrical conductivity of the different MWCNT/PANi composites prepared. The conductivity gradually increases from 0.09 S/cm for pure PANi to 36 S/cm for MWCNT/PANi with MWCNT wt%≤8. The electrical conductivity of MWCNT/PANi with 3 wt% of MWCNT was below 5 S/cm, which then increased upto 36 S/cm for the composite with a MWCNT loading wt% of 8 and more. The abrupt change in the electrical conductivity of PANi after a MWCNT loading of 3wt% could be due to the formation of good conducting paths in the composite [307]. Since there was no further increase in the electrical conductivity of PANi at higher MWCNT loading beyond 8 wt%, the MWCNT/PANi composite with 8 wt% of MWCNT was selected as the filler in the laminate preparation.

![Figure 7-5: DC electrical conductivity of MWCNT/PANi composites (a); DC electrical conductivity of glass fiber reinforced MWCNT/PANi-epoxy laminates (b).](image)

Figure 7-5(b) shows the room temperature electrical conductivity of the glass fiber reinforced MWCNT/PANi-epoxy laminates. Incorporation of MWCNT/PANi nanofillers in general led to substantial increases in the electrical conductivity. The electrical conductivity was increased from 1.25x10^{-10} S/cm for the laminate with unmodified epoxy to 8.75x10^{-5} S/cm for the laminate with MWCNT/PANi (3 wt%) filled epoxy. An abrupt increase in the electrical conductivity was observed for the laminate when the filler loading was varied between 0 and 1.5 wt%. Therefore, from the Figure 7-5 (b) we can infer that the percolation threshold for achieving good electrical conductivity of the laminates lies between 0.25 and 1.0 wt % loading of
MWCNT/PANi contents. When the loading of MWCNT/PANi is higher than 1.5 wt %, the composites show only a slow improvement in the electrical conductivity. A similar trend in electrical conductivity was observed for MWCNT/PANi-modified epoxy composites by Xu et al.[323]. Since MWCNTs are coated by PANi, MWCNTs cannot aggregate in the epoxy resin and thus this can favor the formation of an electrically conductive network. Also the high aspect ratio of the conducting MWCNT/PANi filler in the epoxy resin can improve the electrical conductivity at low levels of filler addition [323].

7.3.3 Mechanical properties

7.3.3.1 Young’s Modulus
The addition of conducting fillers to epoxy matrix is expected to improve the mechanical properties because of the high aspect ratio and highly elastic behavior of the CNTs during loading and the strong interfacial bonding between epoxy and PANi-coated MWCNTs. Two methods were employed to investigate the effect of the addition of fillers on the mechanical properties—tensile test and dynamic mechanical analysis (DMA). Figure 7-6(a) shows the stress-strain curves of different laminates. Figure 7-6(b) shows the variation in Young’s modulus for different laminates prepared (reported averaged values of three different tensile tests). As shown in Figure 7-6(b), the Young’s modulus of the laminates increased from a filler loading of 0.5 to 2.5 wt% in the epoxy. When the content of MWCNT/PANi was higher than 2.5 wt%, there was a marked decrease in the Young’s modulus. The improvement in the Young’s modulus is attributed to the presence of MWCNT/PANi filler as the other reinforcement fiber wt% was constant in all the laminates. In the MWCNT/PANi modified composites, the terminal amino groups of PANi coatings react with the epoxy matrix during curing reactions, which provides interfacial adhesion for load transfer between epoxy and nanotubes leading to increased Young’s modulus at low filler content[322, 323]. But, the resin viscosity was increased at higher loadings of MWCNT/PANi filler (<2.5 wt%) in the epoxy resin and this hindered the layup process of the laminates. The high viscosity of the resin resulting in poor dispersion and poor wetting of the glass fibers could be responsible for the drop off in modulus at 3 wt% loading of MWCNT/PANi. Also, at higher loading of the MWCNT/PANi filler (3 wt. %), the participation of the terminal amino groups of PANi in the epoxy curing reactions, could end up consuming more of the epoxide groups, leading to a weaker matrix. This in turn could also lead to the decrease in the modulus of the matrix at 3 wt% loading of MWCNT/PANi.
7.3.3.2 Dynamic mechanical analysis

The thermo-mechanical performance of the glass fiber-reinforced MWCNT/PANi-epoxy laminates, for different MWCNT/PANi filler contents, was studied using DMA. Figure 7-7, Figure 7-8, Figure 7-9 show the variation of storage modulus, loss modulus and loss tangent as a function of temperature respectively of different laminates.

The storage and loss moduli of the laminates were different in the glassy and rubbery regions. In Figure 7-7, the storage modulus of the laminates in the glassy regions was increased upon the incorporation of MWCNT/PANi filler from 0–1 wt%. This behavior can be attributed to the increased interaction between the MWCNT/PANi and epoxy due to the formation of covalent bonds between them. The interfacial interaction between MWCNT/PANi and epoxy moieties reduces the mobility of epoxy polymer chain in the composite [324] leading to an enhancement in the storage modulus of the laminates. However, at filler content above 1 wt% a reverse effect was observed. This could be due to two reasons. Firstly, the increased viscosity of the resin-filler system above 1 wt% filler content, leading to the poor wetting of the glass fiber reinforcement by MWCNT/PANi modified matrix and hence poor adhesion between epoxy and glass fibers [324]. Secondly, the poor dispersion or agglomeration of the filler in the matrix can lead to the poor covalent interactions between PANi and epoxy. The agglomerated filler particles can alter the flow behavior of the matrix and these could act as centers for stress concentration and can nucleate failure upon loading.
However, above the glass transition temperature i.e. in the rubbery region, a slight increase of storage modulus in the composite was observed with filler loading. The slight enhancement of the storage modulus can be attributed to the relatively higher molecular motion of the polymer in the rubbery region. Montazeri et al. reported that in the rubbery state the molecular motion and its amplitude remains high and the macromolecule is not practically in contact with particles for which no shear force acting between them [325]. The variation of the storage modulus of the laminates in the rubbery region was similar to the variation in the glassy region. Rahman et al. have performed the DMA analysis of amino functionalized-MWCNT incorporated e-glass/epoxy composites. They have found similar behavior at a loading level of 0-0.4 wt% of the filler [324].

![Storage modulus vs. temperature response of the laminates](image)

**Figure 7-7: Storage modulus vs. temperature response of the laminates**

The nature of variation in the loss modulus (Figure 7-8) of the laminates was similar as compared to the variation in the storage modulus. Loss modulus of composites indicates the energy used to deform the material that is dissipated into heat and can be used as a measurement of viscous component or unrecoverable oscillation energy dissipated per cycle. The good dispersed fillers must dissipate energy due to the resistance against viscoelastic deformation of the surrounding matrix [325, 326]. The interaction between amine functionalities of PANi on the MWCNTs and epoxy improve the efficiency of load transfer from matrix to fillers resulting in an increase in loss modulus. At higher loading, the agglomeration of the filler in the matrix can lead to decrease in the loss moduli of the laminates.
The glass transition temperature of polymers is generally affected by a number of factors such as molecular weight, molecular structure, length of side group, presence of double bonds in the backbone, presence of plasticizer, presence of moisture, free volume etc. Free volume is the space arising from the inefficient packing of the disordered polymer chain and this is the space available for the rotation of the polymeric chains. This in turn can lead to the decrease in glass transition temperature [327]. From the Figure 7-9, we can observe a shift of glass transition temperature of the laminates to higher temperatures with the amount of added filler. The glass transition temperature was shifted from 82.4°C for the laminate without filler to 125 °C for the laminate incorporated with 2 wt% of MWCNT/PANi filler. This gain in thermo-stability can again be interpreted as a reduction in mobility of epoxy matrix. The interactions between MWCNT/PANi and epoxy can induce different cross-linking regions in epoxy matrix which will eventually reduce the polymer chain motion. Rahman et al. have observed the $T_g$ at 112°C for the amine-modified MWCNT-incorporated e-glass/epoxy composite. The glass transition temperature of the laminates with 2.5 and 3 wt% of MWCNT/PANi got broadened and slightly reduced as compared to the laminate with 2 wt% of MWCNT/PANi filler. This variation can be explained in terms of increase in the free volume as the function of added fillers. Belaabed et al. have explained the possible cause for the decrease in glass transition temperature of PANi/epoxy composite with the amount of added PANi [319]. Therefore, the increased free volume with
higher loading of MWCNT/PANi (<2wt%) resulted in the increase of motion ability of the polymer chain and thus reduction in glass transition temperature.

![Figure 7-9: Loss tangent (tan delta) vs. temperature response of the laminates](image)

### 7.3.4 Microwave absorption EMI shielding and analyses

The details of the EMI shielding and microwave absorption analyses have been described in the section “5.3.4 EMI shielding and microwave absorption analysis” The Reflection loss can be calculated using scattering parameters $S_{11}$ (or $S_{22}$) and $S_{12}$ (or $S_{21}$) as follows

$$R_L = -20 \log(\Gamma)$$

$$\Gamma = x \pm \sqrt{(x^2 - 1)} \left| \frac{1}{|\Gamma|} \right| \leq 1$$

Where, $x = \frac{(S_{11}^2 - S_{12}^2 + 1)}{2S_{11}}$

The frequency dependence of the reflection loss for the samples in the S-band is shown in the Figure 7-10. Figure clearly demonstrates the effect of increasing amount of filler in the epoxy towards the microwave absorbing ability of the laminates. Minimum reflection loss of the laminate was dependant on the concentration of the filler when the filler loading was low (0–1.5 wt%) and was nearly constant at higher loading of the filler. The reflection loss increased from -16 dB for the laminate with 0.5wt% MWCNT/PANi to -30.1 dB for the one with 2wt% MWCNT/PANi filler.

Materials with electric or magnetic dipoles tend to absorb electromagnetic waves strongly since the dipoles can interact with transverse electric and magnetic vectors of the EM waves leading to
attenuation of the EM waves. In doped ICPs, the losses due to dielectric permittivity are generally higher than the losses associated with the magnetic permeability. Generally, in inherently conducting polymers, besides the doping-induced polarization, filler-induced interfacial polarization may also contribute towards the dielectric permittivity [8]. The increased absorption of EM radiation by MWCNT/PANi filled PS matrix has been demonstrated by Saini et al. [5]. The presence of MWCNT/PANi leads to multiple scattering of EM radiation, resulting in multiple passes of radiation thought the conducting laminate. Each of these passes results in associated absorptions step contributing towards total absorption. Therefore, total absorption is a cumulative effect of aforementioned absorption sub-steps. As we increase the fraction of MWCNT/PANi wt% in the epoxy, the total number of highly conducting component present in the shield increases, leading towards enhancement of absorption. From the reflection loss analysis we can infer the utility of the suggested laminates as structurally strong radar absorbing materials.

![Figure 7-10: Reflection loss of different laminates in the S band](image)

The total EMI shielding effectiveness (SE<sub>T</sub>) of the material will be the sum of shielding effectiveness due to reflection (SE<sub>R</sub>), absorption (SE<sub>A</sub>) and multiple internal reflections (SE<sub>M</sub>).

\[
SE_T = SE_R + SE_A + SE_M
\]

Scattering parameters (S-parameters) of the two-port vector network analyzer (VNA) are S<sub>11</sub> (or S<sub>22</sub>) and S<sub>21</sub> (or S<sub>12</sub>) which are representing reflection and transmission coefficients respectively and from this SE<sub>T</sub> was calculated.
Figure 7-11: \( SE_A \) (a), \( SE_R \) (b) and averaged \( SE_T \) (c) of different laminates in the S-band

Figure 7-11 (a) & (b) shows \( SE_A \) and \( SE_R \) of the laminates with different MWCNT/PANI loadings in the frequency range of 2–4GHz. Figure 7-11 (c) shows averaged \( SE_T \) of laminates with different MWCNT/PANI loading. As shown in Figure 7-11(c), the \( SE_T \) value (averaged) of the laminates increased from 0.5–1.5 wt% of filler in the epoxy and then remains unaltered. The maximum of \( SE_T \) value was \(-7.1\) dB for a sample loaded with 3wt% of MWCNT/PANI. As shown in Figure 7-11 (a) & (b), the SE due to absorption was higher as compared to SE due to reflection, and this may be explained in the terms of increase in conductivity, dielectric losses as well as dielectric permittivity of the laminate as the filler wt% vary from 0.5–3. Further, reflection is surface effect whereas absorption is a bulk related phenomenon. Therefore, the absorption loss rises by much larger magnitude than reflection, both with the increase in concentration of MWCNT/PANI. The results confirm that the observed \( SE_T \) values were dominated by absorption phenomenon. The DC electrical conductivity and \( SE_T \) has shown
similar behavior at filler loading <2 wt%. From this, one can infer the direct correlation between electrical conductivity and SE.

7.4 Conclusions
In this study, the MWCNT/PANi modified matrix was used to prepare the GFRP laminates by wet-layup vacuum bagging method. The amount of the filler (MWCNT/PANi) in the epoxy matrix was varied from 0.5, 1, 1.5, 2, 2.5, 3 wt% with respect to the epoxy-hardener system, where as the fiber amount kept constant in all the laminates. The hybrid laminates were then characterized and microwave absorption analysis has been carried out in the S-band. The electrical and mechanical properties of the laminates got enhanced after the addition of MWCNT/PANi filler in the epoxy matrix. The maximum tensile strength was observed for the laminate with a filler loading of 2wt% MWCNT/PANi in the epoxy and the further addition of the filler decreased the properties of the laminate. The high viscosity of the resin resulting from the poor dispersion of the filler may cause poor wetting of the glass fiber during laminate fabrication and hence poor adhesion between glass fiber and matrix. This may be the factor for the decrease in modulus at 3 wt% loading of MWCNT/PANi. The storage and loss moduli of the laminates were also increased (upto 1.5 wt% of filler) and then decreased at high filler loading (filler loading< 2wt %). The interaction between amine functionalities of PANi on the MWCNTs and epoxy improve the efficiency of load transfer from matrix to fillers resulting in an increase in the moduli at low filler loading. At higher loading, the agglomeration of the filler in the matrix can lead to decrease in the moduli of the laminates. The glass transition temperature was shifted from 83.8°C for the laminate without filler to 136 °C for the laminate incorporated with 3 wt% of MWCNT/PANi filler. This gain in thermo-stability can be interpreted as a reduction in mobility of epoxy matrix due to the interactions between MWCNT/PANi and epoxy. The EMI shielding and microwave absorbing natures of the laminates also got enhanced after the modification of the epoxy matrix. The Minimum reflection loss of the laminate was depend on the concentration of the filler when the filler loading was low (0–1.5 wt%) and was nearly constant at higher loading of the filler. The reflection loss has increased from −16 dB for the laminate with 0.5wt% MWCNT/PANi to −30.1 dB for the one with 2wt% MWCNT/PANi filler. Similarly, the EMI shielding ability was increased due to the addition of the filler to the epoxy. The maximum of SE value (averaged over S-band) was ~ −7.1 dB for a sample loaded with 3wt% of MWCNT/PANi. The improvement in the microwave properties can be directly
correlated with the electrical conductivities of the laminates. The present investigation infers the utility of the MWCNT/PANI modified epoxy/glass fiber laminates as structurally strong radar absorbing materials.