ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XX [2022] | Fascicule 2 [May]

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SYNTHESIS OF CARBON NANOTUBES COMPOSITE TO ENHANCE THERMAL & ELECTRICAL PROPERTIES FOR THE SPACE APPLICATIONS

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Abstract: The high specific stiffness materials are used to design the space payload components. These components should sustain the extreme environmental condition throughout its life cycle without failure. The prerequisites of future space missions need lightweight materials which must be mechanically strong and high thermal and electrically conductive. Carbon fiber reinforced polymer (CFRP) offers considerable mass saving and high strength, which is widely used for space payload components. However, it has limitations to replace the traditional space–qualified materials due to its low conductivity. The Carbon Nanotubes (CNTs) are efficient to enhance greater electrical and thermal conductivity. For the CNTs to be seen as effective reinforcements for attaining high strength and conductivity of polymer composites, they need to meet the criteria of being well dispersed by the solution mixing method. The quality of the CNT nanocomposite relies upon several parameters like the types of CNTs, its purity, aspect ratio, amount of loading, alignment, and interfacial adhesion between the nanotube and polymer. The performance of the CNT–CFRP composite depends on the successful execution of the processing technique. This review paper intends to highlight the enhancement of the mechanical, thermal, electrical properties of the composite, and the challenges to achieving it. This review paper helps to optimize the process parameters to fabricate Space Payload Components, required to replace existing high–density Space Qualified Materials. This review paper should help optimize the process parameters to fabricate Space Payload Components, which can be excellent alternatives to the existing high–density Space Qualified Materials. Also, this review research is the need of the hour for prominent space agencies like ISRO, NASA, etc, for their future interplanetary missions, where payload weight needs to be kept light without making any compromise on the performance index.
Keywords: Carbon Nanotubes (CNTs), CNT Composite, Dispersion, Thermal Properties, Electrical Properties, Space Applications

1. INTRODUCTION

The space agencies always demand high specific stiffness materials to minimize the launching cost, which can be achieved by selecting the high strength and lightweight material. Weight is of paramount importance when it comes to a space payload. It has always been one of the most crucial factors for any structure that is to be operated in space. Because apparently, the mass of the space payload is directly proportional to the cost of the launching of that mission [1]. Nowadays, Carbon–Fiber reinforced polymer (CFRP) is also an excellent candidate for its specific stiffness, it replaces traditional aluminum alloy at various space payload structures [2]. Therefore, the CFRP material is now being broadly promoted by many space agencies like NASA, ISRO, ESA, JAXA for their satellite components [3–4]. However, the major disadvantage of the CFRP material is having significantly lower conductivity because of resin, which results in lower thermal dispersion, electromagnetic shielding, and current carrying capacity in the CFRP components used for low earth orbit and geosynchronous earth orbit space mission [5–6]. Poor thermal and electrical conductivity affects the heat dissipation to maintain thermal balance in the spacecraft structure and surface coating of precious metals by electroplating [7].

Advanced nanofillers like Graphene and Carbon Nanotube (CNT) can increase the conductivity of CFRP [8–10]. CNT has excellent mechanical properties as well as thermal and electrical conductivity, however, their applications in space missions remains a challenge [11–12]. Various research and experimental analysis are going on micro and nanostructure of CNT composite and to investigate the potential applications of CNT composites for space applications specifically for interplanetary missions [13]. CNT fiber composites have a high tensile property which is why it has been successfully used by NASA for manufacturing pressure vessels of the cold gas thrusters systems [3]. In Short, Carbon nanotubes (CNT) can be added to enhance the strength & stiffness and required thermal and electrical properties to CFRP material essential for aerospace structures and payload components.

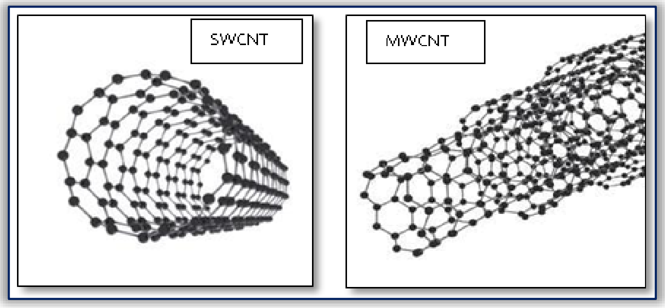

Figure 1. Single Walled Carbon Nanotube & Multi-walled Carbon Nanotubes [17]

Carbon Fibre Reinforced Polymer (CFRP) is one of the most desirable material for space industries due to its high specific stiffness. It is 30% more strong, but five times less in weight compare to traditional space material like Kovar & Invar as shown in Figure 1 [14–15]. For the interplanetary missions where the mass is critical factor of design criteria, CFRP is most advantageous. The major dis–advantage of this material is, it has lower thermal & electrical conductivity compare to other space qualified metal materials[8], As these materials possess thermal and electrical conductivity, which is essential properties for thermal balance by dissipation of heat and surface treatment (electroplating) of precious metals i.e. silver or gold[16]. An Epoxy uses for bonding the Carbon fibre during fabrication of CFRP composite is non–conductive. This epoxy must be conductive to increase the conductivity of CFRP composite. It is possible to use CNTs as filler material to epoxy and enhance the conductivity of CFRP [9–10]. The conductive epoxies are under development and few are available in market but they are expensive. Moreover they should be compatible with space qualified carbon fibres, if not, they must have to undergo space qualification. CNTs can be enforced into CFRP to enhance the mechanical, thermal and electrical properties, required for aerospace industries [17].

Table 1. Physical Properties of Traditional Space material & CFRP [14–15]

Property	Traditional Space Material			Composite (70/30) CFRP Unidirectional
	Aluminum	Kovar	Invar	
Specific Gravity(g/cm^3)	2.7	8.3	8.1	1.6
Young's Modulus (GPa)	70	138	141	181
Electrical Conductivity (S/cm)	2.45 x10^5	0.20 $\times$ 10^5	0.12 $\times$ 10^5	346 Longitudinal 0.01220 Transverse 3.24 x10^{-5} Thru Thick.
Thermal Conductivity (W/mK) at 22 ^{0}C	167	17	13	5–7 in plane 0.5 – 0.8 Transverse
Coefficient of thermal expansion (1/K) PPM	23	5.5	0.5–2	Near 1 35 (Transvers &Thru Thick.)

2. TYPES OF CARBON NANOTUBES (CNTS) AND PROPERTIES

There are two basic structures of CNTs

≡ Single–walled carbon nanotube (SWCNT) and

≡ Multi–walled carbon nanotube (MWCNT) as shown in Figure 1.

A single–walled carbon nanotube (SWCNT) is a seamless cylinder, consists of only one layer of graphene, whereas the multi–walled carbon nanotube (MWCNT) is also cylindrical, with multiple concentric layers of graphene. The SWCNTs have a length in few micrometers whereas its diameter is up to 10 nm [17], whereas the diameters of MWCNT can be up to a few hundred nanometers. It consists of concentric cylinders tubes, which held together by van der Waals forces. [18].

The properties of SWCNT, NWCNT are exceptional specific gravity and conductivity compare with other allotropes of the carbon. It contains remarkable electrical and thermal conductivity as shown in Table 2. The Coefficient of thermal expansion (CTE) of CNT is very low, which is advantageous for the replacement of Invar, space qualified material highly used for optical systems. The space components fabricated by CNT polymer composite, can deliver the sub–system with lowest mass and high performance. The few methods for producing CNTs are laser ablation, arc discharge, and chemical vapour deposition (CVD) [19–20]. The quality and quantity of CNTs depends on its production process. The CVD is best suitable method takes place in vacuum to produce high quality of CNTs.

Table 2. Physical properties of Carbon allotropes [19]

				CNTs	
Property	Fullerene	Graphite	Diamond	SWCNT	MWCNT
Specific Gravity(g/cm^3)	1.7	2	3.5	0.8	1.8
Electrical Conductivity (S/cm)	10^{-5}	4000	10^2–10^{15}	10^2–10^6	10^3–10^5
Thermal Conductivity (W/mK) @ ambient	0.4	298	2000	6000	2000
Coefficient of thermal expansion(1/K) (ppm)	1.7	4–8	1.1–1.3	~0	~0

3. PROCESSING OF CNT–POLYMER COMPOSITES

Fabrication of CNT–Polymer composite depends on the matrix i.e. thermoplastics or thermosetting [30]. The three main processing techniques incorporate the solution mixing, in situ polymerization, melt blending and chemical modification processes, which present some distinct advantages in the manufacturing process of CNT/ Polymer composite. Although the Solution Mixing process produces high–quality composite, apparently the process of Melt Blending is less complicated and it also presents the option of producing the composites on a large scale basis. And on the other hand, the process of In Situ Polymerization helps to produce polymers that exhibit high mechanical properties because of the formation of a covalent bond between the CNT and the polymer matrix. However, this also negatively influences the electronic properties of the composite. Now, to manufacture CNT / Polymer composites both, organic and aqueous medium have been used. The following are the major factors that affect the microstructure development of CNT/polymer composite fiber [21]:

- CNT structure
- Polymer CNT interfacial micro structure
- Dispersion of CNT
- Polymer and CNT orientation.

Due to strong Van der Waals binding energy associated with CNT agglomerates, to separate nanotubes shear mixing or ultrasonication are used, it should be more input mechanical energy for satisfactory dispersion [30]. A good dispersion aids in preventing the stress concentrators and the slippage of the nanotube as well. This results in more filler surface area during the composites loading. This can increase the performance of the composites to a great level. However, the dispersion process also throws in some challenges like the length of the nanotubes, their entanglement, volume fraction, and high viscosity. CNT with more length obstructs the separation of the tubes which results in more shear force that's required to separate the agglomerates and to disperse the individual CNTs.

— Dispersion

Different methods such as mechanical stirring, ultrasonication, calendaring, or combination of these methods lead to improve CNTs dispersion but it can cause the CNTs damage. Very high shear forces may result in the destruction of or some sort of damage to the structure of the CNT, which in turn can highly affect the conductivity of the composite. However, to enhance the property, the process of surface modification of CNTs may prove helpful. Although, the composites with non–modified CNTs reveal higher electrical conductivity [22]. There is a threshold limit of CNT content to achieve mechanical, thermal, and electrical properties. More addition of CNT prevents the formation of homogeneous dispersions and the removal of large volumes of solvents [12]. Table 3 shows how the dispersion affects the mechanical, thermal, and electrical properties. Well dispersed CNTs increase the strength of polymers and thermal conductivity approx. more than 33% and 45% respectively, whereas electrical conductivity significantly increases with the addition of the lowest %wt CNTs. However, well dispersion is the biggest challenge to achieve maximum advantage of CNTs.

Table 3. Comparison table of well dispersed and poorly dispersed CNTs [23]

CNT Contain % wt	Tensile Strength MPA		Thermal conductivity W/mK		Electrical conductivity S/cm	
	Poor Dispersed	Well Dispersed	Poor Dispersed	Well Dispersed	Poor Dispersed	Well Dispersed
0.5	69	73	0.13	0.20	$1.00E^{-02}$	$2.00E^{-02}$
1	64	75	0.16	0.23	$1.50E^{-02}$	$4.00E^{-02}$
1.5	60	80	0.18	0.26	$2.00E^{-02}$	$5.00E^{-02}$

— Gel time

Gel time is also one of the important factors of epoxy, directly proportional to the CNT contain, The addition of CNTs reduces gel time more than 3 times for 1 wt.% of CNTs. Gel time is approx. 1200 s for the epoxy (without CNTs) whereas it reaches 360 s for 1 wt.% of CNTs as shown in Figure 2. The decrement of gel time leads to the formation of defects such as voids, bubbles, and other structural discontinuities, which can influence the thermal and electrical conductivities [22–23].

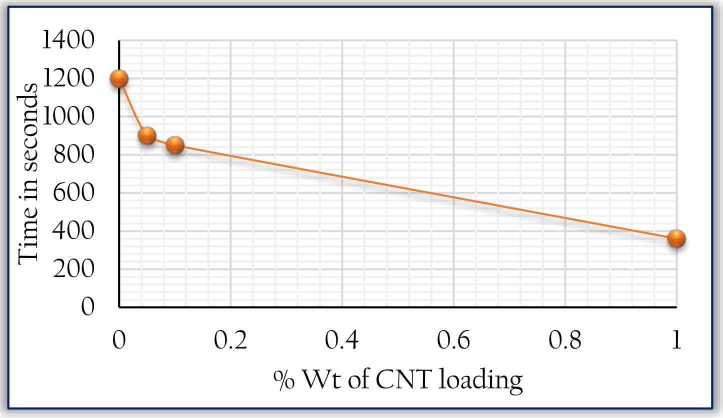

Figure 2. Gel Time Vs. CNT Amount [20]

— Sonication

The CNTs agitation in polymer matrix is carried out by ultrasound energy called ultra–sonication process. The frequency more than 20 Khz is used by ultrasonic probe or bath. The dispersion of CNTs in a small volume and less viscous form of solution can be possible by this process. This ultrasonic probe produces high impact energy with a low amount of the shear forces, which may not be sufficient to proper dispersion. Researcher uses combine process mixing and sonication to ensure all the polymer passes through this volume. There are two types of sonication methods:

- Mild sonication
- High power sonication.

High power sonication may damage the length of a nanotube, which can directly affect the composite properties [23–25].

Generally, Aceton or ethanol is used as a solvent in the sonication process to produce CNT composite. In first stage, the solvent separates the agglomerated CNTs and then mixes polymer. Advantages of this solvents are:

≡ To separate the agglomerated CNTs
≡ Low boiling point tends to evaporate solvent rapidly.

The result of sonication process (dispersion quality) can be analysed by morphological study and evaluation of physical properties.

— Thermal Properties

a) Thermal Conductivity

Enhancement of thermal properties, required for fabrication of Space Payload Components can be possible by the addition of CNTs. It increases thermal conductivity, thermal diffusivity, and glass transition whereas it reduces the coefficient of thermal expansion (CTE), significant required property for the material of interplanetary missions. The addition of even 1 wt.% of single–wall CNTs increases the thermal conductivity of epoxy resin twice, on the contrary to the same weight fraction of carbon fibers, which increased the thermal conductivity of approx. 40% [24].

The thermal properties directly depend on the types of CNTs contain polymer composite. However, for the SWCNT, there is no significant increase in thermal conductivity even with 5%wt of loading, but further loading of SWCNT (7%wt) increases the thermal conductivity drastically, whereas 0.2% of MWCNT can increase thermal conductivity significantly, this rise can be seen up to 1% of the threshold limit as shown in Figure 3. Thus MWCNT is the most suitable CNTs to improve the thermal conductivity[26]. The improvement of thermal conductivity leads to increase the heat dissipation results to increment of thermal stability of composite, which is essential for the space components.

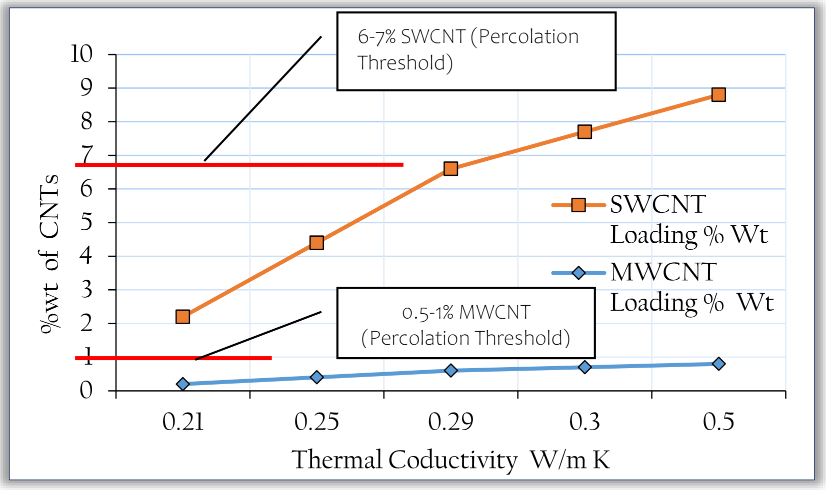

Figure 3. Thermal Conductivity vs. SWCNT & MWCNT Loading [24][26]

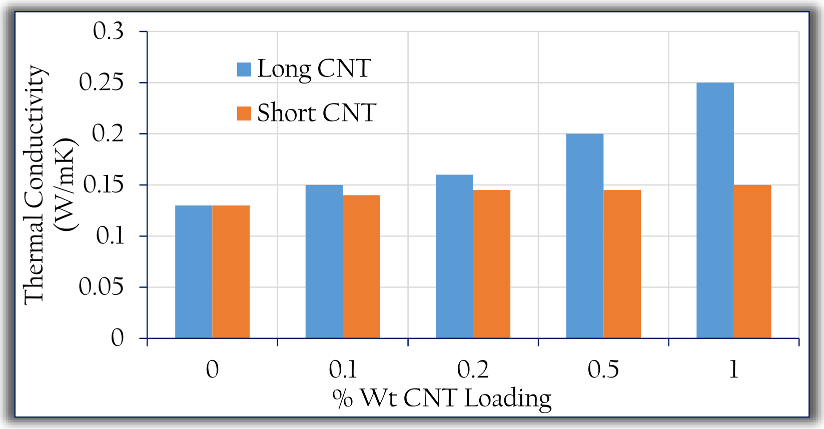

Figure 4. Thermal Conductivity vs. Long & Short CNT Loading [28]

The length (L) and diameter (D) of CNTs affects the thermal conductivity of the composite. The thermal conductivity is more in the long aspect ratio (L/D=500) than that of short aspect ratio (L/D=50)[28] as shown in Figure 4.

b) Thermal Diffusivity

Thermal conductivity (λ) is directly proportional to thermal diffusivity (α) and inversely proportional the density (ρ) and Specific heat capacity (Cp) at different temperature. Thermal diffusivity is measured by experience analysis at the temperature 25, 65, 100 and 140°C [24]. Thermal diffusivity is increases drastically at 0.2% CNT, then it gets stabilized up to 1% as shown in Figure 5.

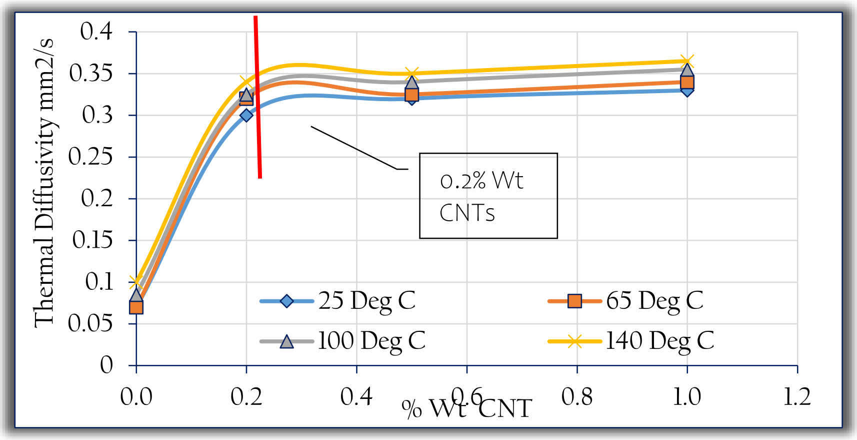

Figure 5. Thermal Diffusivity with temperature with different % of CNT amount [24]

c) Coefficient of Thermal Expansion

Satellite in Low Earth Orbit (LEO) passes in and out of the earth's shadow as a result of which the exterior surface is exposed to long–term periodic temperature fluctuations and thermal stresses are induced by these thermal changes due to anisotropic nature of composite (e.g. large difference in CTE of fiber and matrix). Therefore, thermal fatigue is the major concern for the design of composite material for space payload applications. Thermal experiments demonstrate that the MWCNT–CFRP is thermally stable up to 354ºC. It can survive the thermal cycling in a range of –40ºC to 120ºC without any detectable cracking and de–lamination. It has considerably lower CTE (3.1–3.4 ppm/ ⁰C) than that of Al alloy (24 ppm/⁰C), require value for the Electromechanical Packages for payloads [8].

— Electrical Properties

The material with properties like high electrical conductivity, electromagnetic interference (EMI) shielding, electrostatic dissipation is preferable for the space applications. Traditional space materials like Aluminum, Kovar, and Invar are having high electrical conductivity and low surface resistivity. The SWCNT is the best option to improve these properties in CFRP. The electrical conductivity of composite can sharply increase by the addition of 0.3 to 0.5%wt SWCNTs. SWNT loading, indicating a percolation threshold of ~0.5wt% [29] as shown in Figure 6. The MWCNT (1% Wt) increases the electrical conductivity of composite significantly, however, its percolation threshold is 2.5% higher than SWCNT [24][27] as shown in Figure 7.

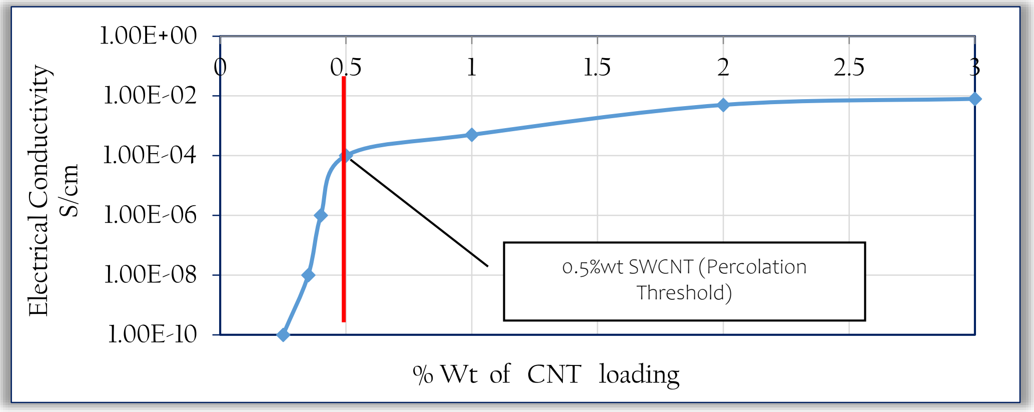

Figure 6. Electrical Conductivity Vs %wt SWCNT loading [29]

The length of CNTs, waviness, thin interphase, and homogeneous dispersion are factors to affect the electrical conductivity. The waviness is inversely proportional whereas length of CNT and homogeneous dispersion is directly proportional to conductivity. Thick interphase CNTs increases the conductivity [17][31].

The volume resistivity and surface resistivity of pure epoxy is 162 times and 8 times more than that of the well–dispersed raw SWCNT (0.5%wt) in epoxy [9] as shown in Table 4. The experimental analysis demonstrated that the amount 0.1% wt of SWCNT concentration in CNT/epoxy composite reduces volume resistivity significantly whereas 1% to 2% of MWCNT form conductive chain in composite results to decreases the volume resistivity as shown in Figure 8. The experimental analysis demonstrated that the resistivity of CNT composite samples decreases drastically with an increase in voltage and %wt concentration [32]. Moreover, the AC conductivity of epoxy increases with the increment of the amount of loading and frequency [27].

Table 4 : Difference between Pure Epoxy and Epoxy with CNT Raw[9]

Sample	Volume Resistivity (ohm–cm)	Surface resistance $1cm^2$ area (ohm)
Epoxy Pure	1.31×10^{11}	7.1×10^9
Epoxy– CNT–Raw	0.8×10^9	0.9×10^9

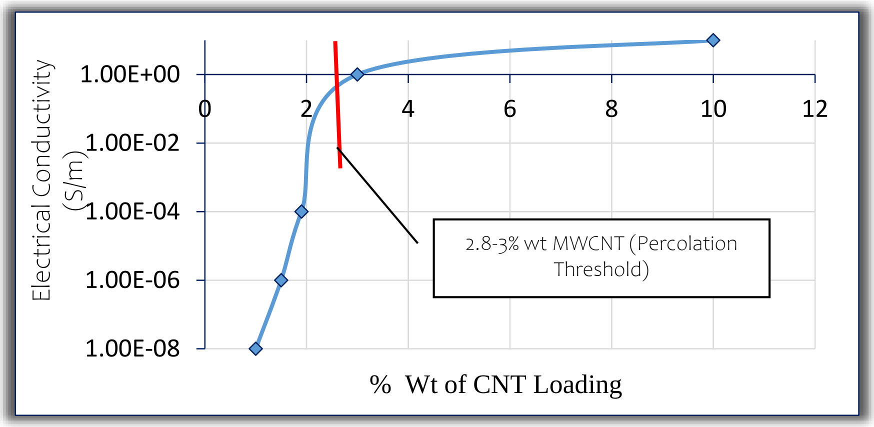

Figure 7. Electrical Conductivity Vs %wt MWCNT loading [27]

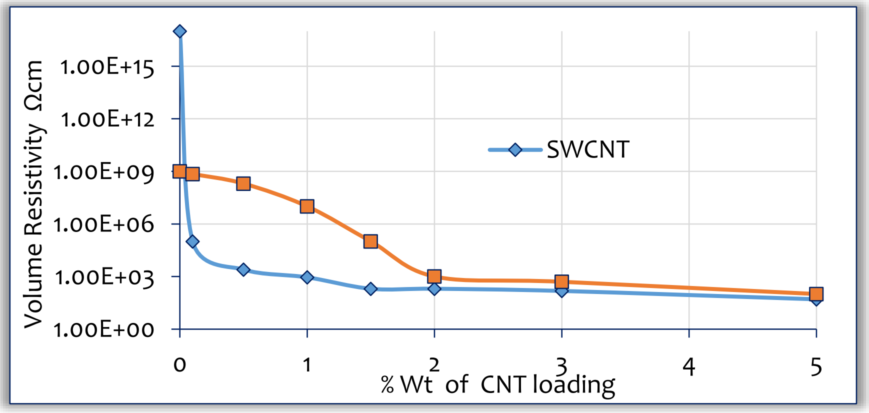

Figure 8. Volume Resistivity Vs amount of SWCNT & MWCNT [9]

Microwave packages, feed, Antennas of space payloads are fabricated by the material which is mechanical strong and provides acceptable shielding effectiveness (SE). The electronic package fabricated by neat CFPR can degrade SE. The enforcement of CNT in CFRP can enhance electrical conductivity, which provides adequate shielding. The Reinforcement of the long and short CNTs affect the EMI shielding and electrostatic dissipation (ESD) of the CNT composite. However, short CNTs can make conductive composite, suitable only for ESD. The CFRP material reinforced with MWCNT (0.2%) provides higher EMI SE (~ –80 dB) than Al6061–T6 [29].

— Mechanical properties

The mechanical properties of composite like tensile strength and yield strength increases with increment of %wt SWCNT. It is also dependent on homogeneous dispersion and orientation of SWCNT polymer contains 0.2% of MWCNTs can improve the strength approx. 46% in comparison to neat CFRP and double the tensile strength than that of Aluminum alloy as shown in Table 5. The Vickers hardness is increased by 3.5 times when 2%wt of SWCNT reinforced in polymer. Moreover bending strength is increased up to 0.5% CNT, further addition cause the decrement in strength due to formation of defects [24].

Table 5. Comparison of parameters between Al6061T6, Neat CFRP, MWCNT CFRP[29]

Parameter	Al Alloy	Neat CFRP	MWCNT–CFRP	Comparison with MW CFPR
Tensile Strength (MPa)	320	415	606	89% more than Al Alloy
Young's Modulus (GPa)	68	52	66	Approx Same
Poison Ratio	0.33	0.30	0.30	
Flexural Modulus (GPa)	–	15	30	Double than Neat CFRP
Specific Stiffness $(m^2/s^2)10^6$	25.9	35.8	45.5	75% more than Al Alloy

4. CONCLUSIONS

Until now, Nanotechnology has been chosen by space agencies to accomplish many remarkable missions. CFRP composite is widely used for space payload, where mass is critical design criteria. A carbon nanotube (CNT) is improves the Thermal and Electrical properties of an epoxy resin of CFRP. The advancements in this field of 'Carbon Nanotechnology' offer a great opportunity to space industries to investigate the potential applications for interplanetary missions [32].

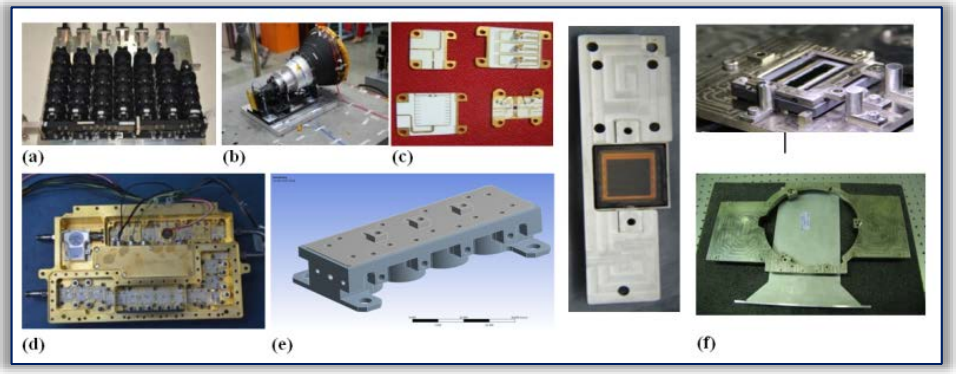

Figure 9. a) Mux filter b) Feed horn c) Carrier plate d) Electromechanical Package e) RF Package f) Invar Structures for Optics [33]

This review plays a vital role to explore the applications of CNT composites for the space payloads components, used for the communications, navigations, and interplanetary missions e.g. Structure, Electronics & RF packages, Microwave Components. Moreover, this can replace the high density of traditional space material.

1. Electromechanical packages and Carrier Plates, RF Filter Cavities, Invariable Dimension Brackets and Housing for Optics, Feed System etc. can be fabricated by CNT–CFRP composite as shown in Figure 9 [33]. With this, it greatly impacts on the tremendous weight reduction of the payload. This composite satisfies the requirement of electromagnetic shielding effectiveness, thermal conductivities, low coefficient of thermal expansions and electrical resistivity for the space payload components.
2. The major advantage to make surface of CFRP electrical conductive is surface coating. The conductive surface can electroplate easily as silver and gold plating are essentials for space components [34]. This increases the RF performance of the payload.
3. High Thermal Conductivity of Composite improves the heat dissipation to maintain thermal balance within payload components, which can reduced the installation of heaters and heat dissipation systems.
4. Intensive study of synthesis process for CNT–CFRP composite resulted:

≡ Before the fabrication of composite, the epoxy enforced CNTs has to be characterized by testing mechanical properties, dimensional stability, and measuring of thermal and electrical properties. Scanning electron microscopy is used for observations to evaluate the CNTs dispersion. The bending strength, thermal and electrical conductivities of the CNT epoxy matrix can be measured & evaluated.

≡ As significant improvement in electrical conductivity is observed at very low CNT loading for SWCNT (0.3–0.5%wt) and MWCNT (1–3% wt). Whereas for enhancement of thermal conductivity CNT loading for SWCNT (>5 % wt), but it is very low in case of MWCNT (0.5%–1%wt) as shown in Figures 3, 6 and 7.

≡ Solution mixing is the easy method for the fabrication of CNT/polymer nanocomposites. It is very common and suitable for small size of samples. The dispersion process with a suitable solvent like Aceton or Propanol, used to reduce the viscosity, can be carried out by mechanical mixing, magnetic stirring or sonication. The process of dispersing the nanotubes is relatively easy with the polymer solution. However, it depends on factors like the CNTs type, its amount in polymer and processing conditions.

≡ CNT is an ideal filler nanomaterial to fabricate polymer composite but there are two major challenges i.e.:

1) Uniform dispersion

2) Adhesion between polymer and CNTs, that need to be addressed and some properties need to be studied before the realization of CNT polymer nanocomposite. These two uncertainties are often problematic at the stage of fabrication of CNT composite.

This review is essential to understand the effects of the parameters on dispersion and it's impact on the process in terms of influencing the thermal and electrical properties of the composite. It is also helpful in analyzing the effect of the amount of CNT disperse on the composites' properties.

This study is useful to achieve the required thermal and electrical properties in CNT polymer composite. This can be later validated by characterization. This detailed analysis can be beneficial in fabricating the space components for the future interplanetary space missions.

Acknowledgment

We are thankful to Shri. B Satyanaranaya, Head QAMD, Shri. KB Vyas, Group Director SRA, Shri. AK Lal, Deputy Director SRA of Space Applications Centre –ISRO for the support, Dr. BS Munjal, Head SSD of Space Applications Centre–ISRO for their guidance and valuable suggestions. We would like to offer our gratitude to Shri. NM Desai, Assoc. Director & Shri. DK Das, Director, Space Applications Centre (ISRO) Ahmedabad.

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