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Carbon Nanotube Composites to Enhance Thermal and Electrical Properties for Space Applications - A Review

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ABSTRACT

High specific stiffness materials are used to design the space payload components. These components should sustain the extreme environmental conditions throughout their life cycle, without failure. Space missions need lightweight materials which are mechanically strong with high thermal and electric conductivities. 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. Carbon Nanotubes (CNTs) are efficient with greater electrical and thermal conductivities. For 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 type of CNTs, 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. It has been intended in this review paper to highlight the enhancement of the mechanical, thermal and electrical properties of the composite, and the challenges in achieving it. An attempt has been made to optimize the process parameters to fabricate space payload components which can be excellent alternatives to the existing high-density materials. Moreover, this review research is the need of the hour for prominent space agencies such as ISRO and NASA for their future inter-planetary missions, where payload weight needs to be kept light without making any compromise on the performance index.

Keywords: Carbon Nanotubes; 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 high strength and lightweight materials. 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; apparently, the mass of the space payload is directly proportional to the cost of launching (Ramamurthy, 2015). Nowadays, Carbon Fiber Reinforced Polymer (CFRP) is an excellent candidate for its specific stiffness and it replaces traditional aluminum alloy in various space payload structures (Marta *et al.* 2018). Hence, CFRPs are being broadly promoted by many space agencies like NASA, ISRO, ESA and JAXA for their satellite components (NASA, 2017; Omid, 2014). However, the major disadvantage of the CFRP material lies in its 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 missions (IRSMP 2018; Robert, 2014). Poor thermal and electrical conductivities affect the heat dissipation to maintain thermal balance in the spacecraft structure and surface coating of precious metals by electroplating (Joana *et al.* 2019).

Advanced nanofillers like graphene and Carbon Nanotubes (CNTs) can increase the conductivity of CFRP (Fawad *et al.* 2015; Sagar Roy *et al.* 2018). CNTs have excellent mechanical properties as well as thermal and electrical conductivity; however, their applications in space missions remain a challenge (Wu, 2012; Irina, *et al.* 2019). Various research and experimental analysis are going on micro- and nano-structures of CNT composites to investigate the potential applications of CNT composites for space applications specifically for interplanetary missions (Jamshid and Emilie, 2017).

CNT fiber composites have a high tensile property – the reason why they have been successfully used by NASA for manufacturing pressure vessels of the cold gas thruster systems (NASA, 2017). In short, CNTs can be added to enhance the strength, stiffness and the required thermal and electrical properties to CFRP material, essential for aerospace structures and payload components.

CFRP is one of the most desirable materials for space industries due to its high specific stiffness. It is 30% more strong, but five times less in weight compared to traditional space material like Kovar and Invar, as shown in Table 1 (Yeqing, 2017; Davis, 2000). For the interplanetary missions, where the mass is a critical factor of design criteria, CFRP is most advantageous. The major disadvantage of this material lies in the fact that it has lower thermal and electrical conductivities compared to other space qualified metal materials (Fawad, *et al.* 2015, Dhaval *et al.* 2020). An epoxy used for bonding the carbon fibre during the 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 materials to epoxy and enhance the conductivity of CFRP (Sagar *et al*. 2018; Yelda *et al*. 2016). The conductive epoxies are under development; a 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 qualifications. CNTs can be enforced into CFRP to enhance the mechanical, thermal and electrical properties, required for aerospace industries, according to Aidin Mehdipou (2011).

Table 1. Physical properties of traditional space materials and CFRP (Yeqing, 2017; Davis, 2000)

Property	Traditional space material			CFRP (Uni-directional)
	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 x 10^5	0.20 x 10^5	0.12 x 10^5	346 longitudinal 0.01220 transverse 3.24 x 10^{-5} thru-thick
Thermal Conductivity (W/mK) @ 22 °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 (transverse and thru-thick)

2. TYPES OF CARBON NANOTUBES (CNTS) AND PROPERTIES

There are two basic structures of CNTs: 1) Single-walled carbon nanotubes (SWCNTs) and 2) Multi-walled carbon nanotube (MWCNTs) as shown in Fig 1. SWCNT is a seamless cylinder, consisting of only one layer of graphene, whereas MWCNT is cylindrical, with multiple concentric layers of graphene. SWCNT has a length in few micrometers whereas its diameter is up to 10 nm (Aidin, 2011), whereas the diameter of MWCNT can be up to a few hundred nm. MWCNTs consist of concentric cylindrical tubes, which are held together by van der Waals forces. (Gerald *et al.* 2017).

The properties of SWCNT and MWCNT are exceptional specific gravity and conductivity compared with other allotropes of the carbon. They contain remarkable electrical and thermal conductivities, as shown in Table 2. The coefficient of thermal expansion (CTE) of CNT is very low, which is advantageous for the replacement of Invar, highly used for optical systems. The space components fabricated by CNT polymer composites, can deliver the sub-system with lowest mass and high performance. The few methods for producing CNTs are Laser ablation, Arc discharge and Chemical vapor deposition (CVD) (Sang-Ha *et al*. 2011; Garima *et al*. 2014). The quality and quantity of CNTs depend on the production process. CVD is the best-suited method since it takes place in vacuum to produce high-quality CNTs.

2.1 Processing of CNT Polymer Composites

Fabrication of CNT-polymer composite depends on the matrix - thermoplastics or thermosetting (Yan *et al*. 2011). The three main processing techniques are Solution Mixing, *In Situ* polymerization and Melt Blending.

Table 2. Physical properties of carbon allotropes (Sang-Ha *et al.* 2011)

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	102-1015	102-106	103-105
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

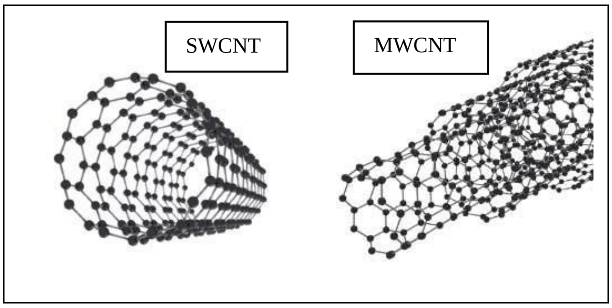

Fig. 1: Single-walled carbon nanotube and Multi-walled carbon nanotubes (Aidin, 2011)

Although Solution Mixing process produces high-quality composites, apparently the process of Melt Blending is less complicated and it also presents the option of producing the composites on a large-scale basis. 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 negatively influences the electronic properties of the composite. Now, to manufacture CNT / Polymer composites, both organic and aqueous media are being used.

The following are the major factors that affect the microstructure development of CNT/polymer composite fiber (Kenan *et al.* 2013):

1) CNT structure
2) Polymer-CNT interfacial micro-structure
3) Dispersion of CNT
4) Polymer and CNT orientation.

Due to strong Van der Waals binding energy associated with CNT agglomerates, to separate nanotubes, shear mixing or ultra-sonication is used (Sang-Ha *et al.* 2011). A good dispersion aids in preventing the stress concentration and the slippage of the nanotubes 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. CNTs with more length obstruct the separation of the tubes, resulting in more shear force requirement to separate the agglomerates and to disperse the individual CNTs.

2.2 Dispersion

Different methods such as mechanical stirring, ultra-sonication, calendaring or combination of these methods lead to improvement in CNT dispersion, but they can cause the damage of CNTs. Very high shear forces may result in the destruction or 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. The composites with non-modified CNTs reveal higher electrical conductivity (Simcha *et al.* 2012). 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 (Irina *et al.* 2019). Table 3 shows how the dispersion affects the mechanical, thermal and electrical properties. Well-dispersed CNTs increase the strength of polymers and thermal conductivity approximately 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 of Poorly dispersed and Well-dispersed CNTs (Kenan *et al.* 2013)

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

2.3 Gel Time

Gel time is also one of the important factors of epoxy; it is directly proportional to the amount of CNT. The addition of CNTs reduce gel time more than 3 times for 1 wt. % of CNTs. Gel time is approximately 1200 s for the epoxy (without CNTs) whereas it reaches 360 s for 1 wt. % of CNTs as shown in Fig. 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 the electrical conductivities (Simcha *et al*. 2012; Bal and Samal, 2007).

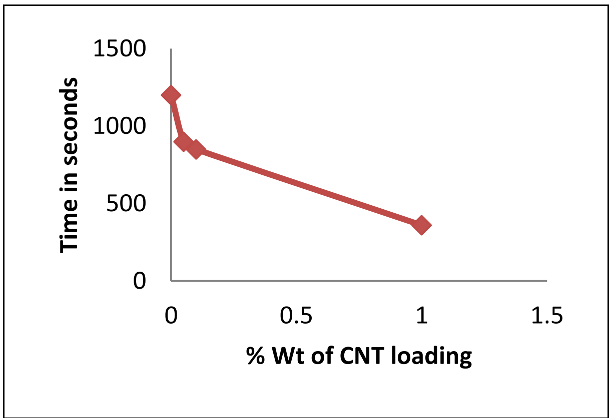

Fig. 2: Gel time vs. CNT amount

2.4 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. Researchers use combined process - mixing and sonication, to ensure that all the polymers pass through this volume. There are two types of sonication methods: 1) Mild sonication and 2) High-power sonication. High-power sonication may damage the length of nanotubes, which can directly affect the composite properties (Bal and Samal, 2007; Ewelina *et al*. 2014; Veena and Anju, 2011).

Generally, acetone 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:

1) They separate the agglomerated CNTs.

2) 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.

2.5 Thermal Properties

2.5.1 Thermal conductivity

Enhancement of thermal properties, required for the fabrication of space payload components, is possible by the addition of CNTs. It increases thermal conductivity, thermal diffusivity and glass transition, whereas it reduces the coefficient of thermal expansion (CTE), a significantly required property for the materials used for interplanetary missions. The addition of even 1 wt. % of SWCNTs increases the thermal conductivity of epoxy resin twice, on the contrary to the same weight fraction of carbon fibres, which increased the thermal conductivity by approximately 40% (Ewelina *et al.* 2014).

The thermal properties directly depend on the type of CNTs in polymer composites. However, for the SWCNTs, 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 Fig. 3. Thus, MWCNTs are the most-suitable CNTs to improve the thermal conductivity (Du *et al*. 2006). The improvement of thermal conductivity leads to increase in the heat dissipation, resulting in increment of thermal stability of composites, which is essential for the space components.

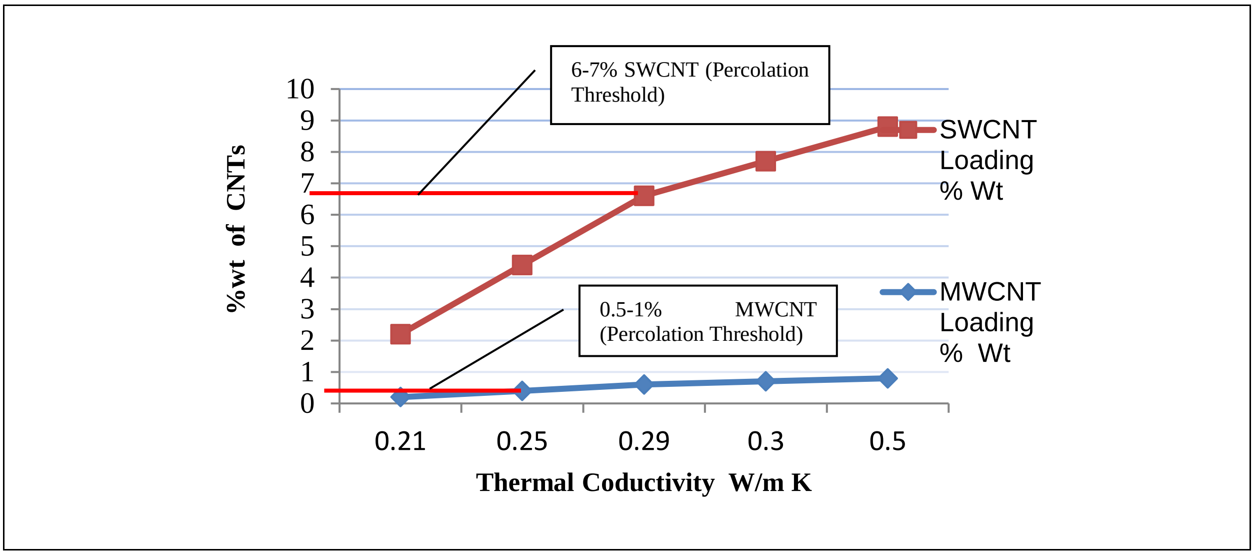

Fig. 3: Thermal conductivity vs. SWCNT and MWCNT loading (Ewelina *et al.* 2014; Du *et al.* 2006)

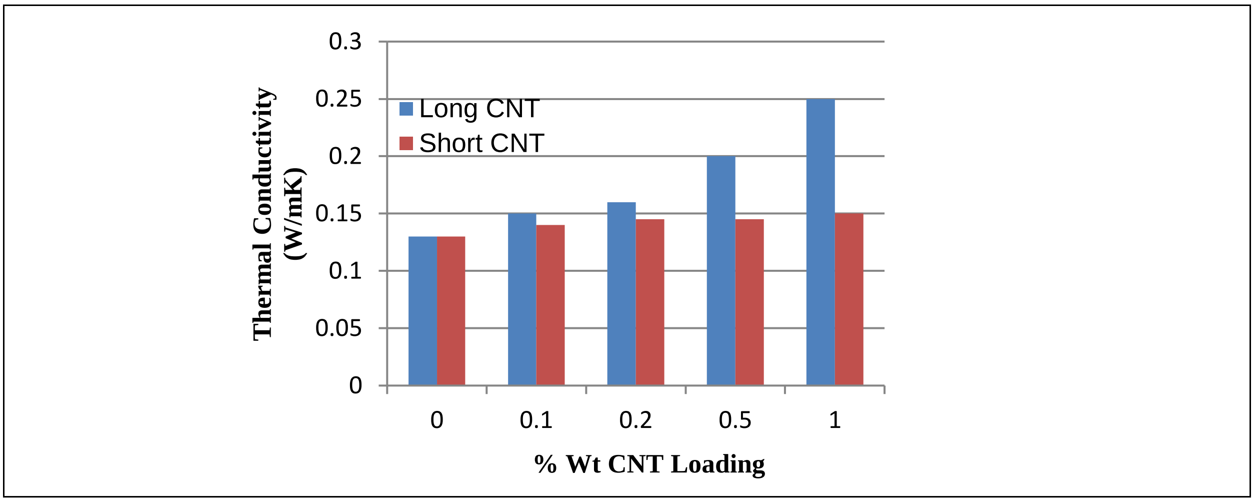

Fig. 4: Thermal conductivity vs. Long CNT / Short CNT loading (Michael *et al.* 2013)

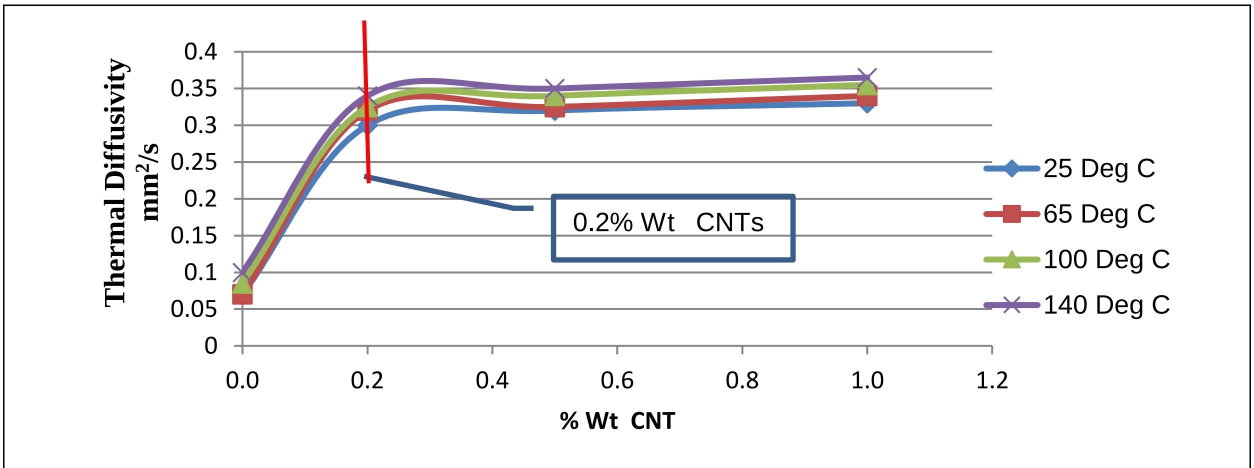

Fig 5. Thermal diffusivity vs. % wt. of CNTs at various temperatures

The length (L) and diameter (D) of CNTs affect 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) (Michael, 2013), as shown in Fig. 4.

2.5.2 Thermal diffusivity

Thermal conductivity (λ) is directly proportional to thermal diffusivity (α) and inversely proportional the density (ρ) and specific heat capacity (C_p), at different temperatures. Thermal diffusivity is measured by experience analysis at the temperature 25, 65, 100 and 140 °C (Ewelina *et al*. 2014). Thermal diffusivity increases drastically at 0.2% CNT, then it gets stabilized up to 1%, as shown in Fig. 5.

2.5.3 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; 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 354 ºC. It can survive the thermal cycling in a range of -40 ºC to 120 ºC, without any detectable cracking and de-lamination. It has considerably lower CTE (3.1-3.4 ppm/ºC) than that of Al alloy (24 ppm/ºC), required for the electromechanical packages for payloads (Fawad, *et al*. 2015).

2.6 Electrical Properties

Materials with properties like high electrical conductivity, electromagnetic interference (EMI) shielding and electrostatic dissipation are 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 composites can sharply increase by the addition of 0.3 to 0.5 % wt. SWCNTs. SWNT loading, indicating a percolation threshold of ~0.5 wt. % (Fawad *et al*. 2017), is shown in Fig. 6. MWCNT (1% wt.) increases the electrical conductivity of composites significantly; however, its percolation threshold is 2.5% higher than SWCNT (Ewelina *et al*. 2014; Nicoletto, 2015), as shown in Fig. 7.

The length of CNTs, waviness, thin interphase and homogeneous dispersion are the factors affecting the electrical conductivity. The waviness is inversely proportional, whereas length of CNT and homogeneous dispersion are directly proportional to conductivity. Thick interphase CNT increases the conductivity (Aidin, 2011; Songlin *et al*. 2019).

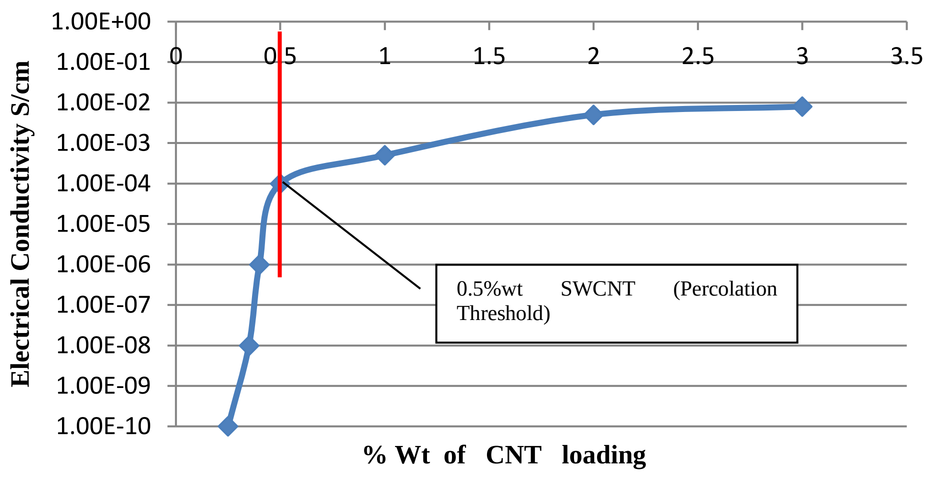

Fig. 6: Electrical conductivity vs. % wt. of SWCNT loading (Fawad *et al.* 2017)

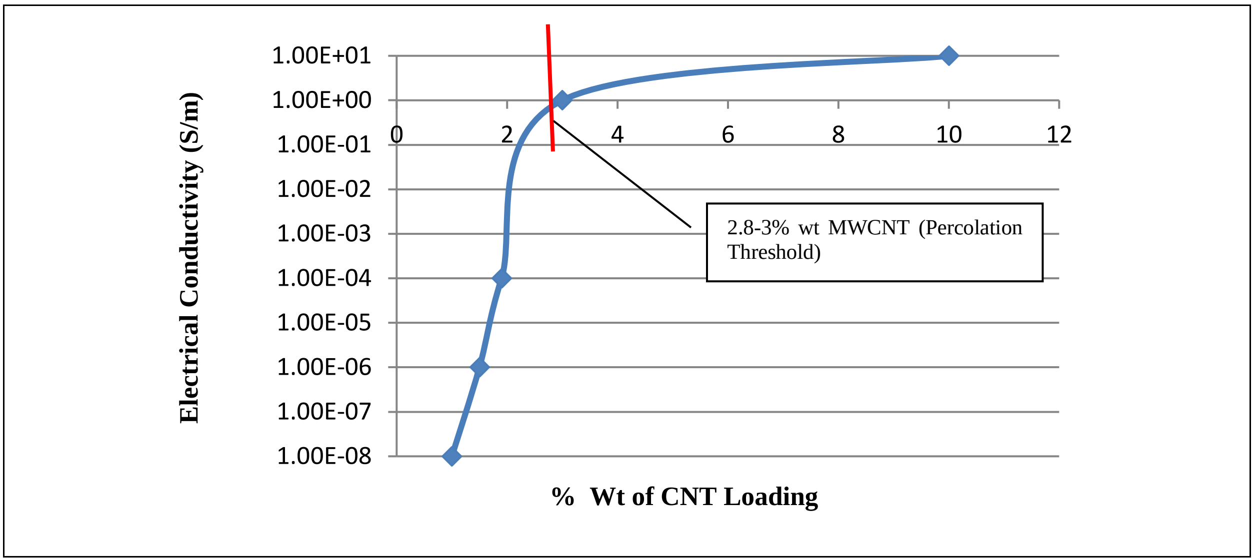

Fig. 7. Electrical conductivity vs. % wt. MWCNT loading (Nicoletto *et al.* 2015)

Table 4. Difference between pure epoxy and epoxy with CNT raw (Sagar, 2018)

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

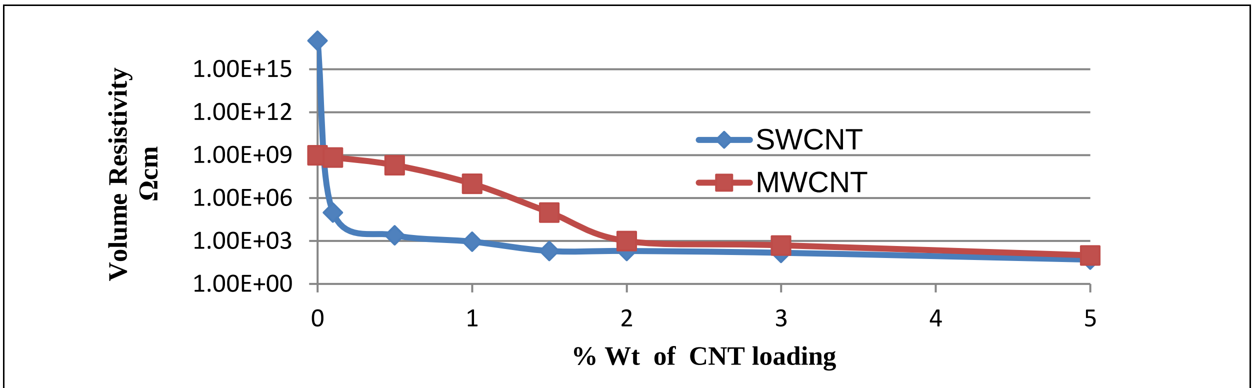

Fig 8. Volume resistivity vs. Amount of SWCNT and MWCNT (Sagar, 2018)

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, respectively (Sagar *et al*. 2018), as presented in Table 4. The experimental analysis has demonstrated that 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, resulting in decrease of the volume resistivity as shown in Fig. 8. The experimental analysis demonstrated that the resistivity of CNT composite samples decreases drastically with an increase in voltage and % wt. concentration (Suraj *et al*. 2013). Moreover, the AC conductivity of epoxy increases with the increment of the amount of loading and frequency (Nicoletto *et al*. 2015).

Microwave packages, feeds and antennas of space payloads are fabricated by the materials which are mechanical strong and provide acceptable shielding effectiveness (SE). The electronic package fabricated by neat CFRP 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 (Fawad *et al*. 2017).

2.7 Mechanical properties

The mechanical properties of composites like tensile strength and yield strength increases with increment in % wt. of SWCNT; they are also dependent on homogeneous dispersion and orientation of SWCNT. Polymers containing 0.2 wt. % of MWCNTs can improve the strength approx 46% in comparison to neat CFRP and has double the tensile strength than that of Aluminum alloy, as evident from Table 5. The Vicker's hardness is increased by 3.5 times when 2% wt. of SWCNT is reinforced in polymer. Moreover, bending strength is increased up to 0.5% CNT; further addition causes the decrement in strength due to formation of defects (Ewelina *et al.* 2014).

Table 5. Comparison of parameters between Al6061T6, Neat CFRP and MWCNT CFRP (Fawad, 2017)

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	Approximately same
Poison Ratio	0.33	0.30	0.30	Approximately same
Flexural Modulus (GPa)	-	15	30	Double than Neat CFRP
Specific Stiffness (m2/s2) 106	25.9	35.8	45.5	75% more than Al Alloy

3. CONCLUSIONS

Until now, nanotechnology has been chosen by space agencies to accomplish many remarkable missions. CFRP composites are widely used for space payload, where mass is a critical design criterion. A carbon nanotube (CNT) 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 (Suraj, 2013).

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 (structural, electronics and RF packages and microwave components). Moreover, they can replace the traditional space materials.

1. Electromechanical packages and carrier plates, RF filter cavities, invariable dimension brackets and housing for optics, feed systems, etc., can be fabricated by CNT-CFRP composites as shown in Fig. 9 (Dhaval A. Vartak *et al.* 2020). With this, it greatly impacts the weight reduction of the payload. These composites satisfy the requirement of electromagnetic shielding effectiveness, thermal conductivities, low-coefficient of thermal expansion and electrical resistivity for the space payload components.

2. The conductive surface of CFRP can be electroplated easily; silver and gold plating are essential for space components (Lonjon, Antoine 2012). This increases the RF performance of the payload.

3. High thermal conductivity of composites improves the heat dissipation to maintain thermal balance within payload components, which can reduce the installation of heat dissipation systems.

Before the fabrication of composite, the epoxy enforced CNTs have 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 dispersion of CNTs. The bending strength and thermal and electrical conductivities of the CNT-epoxy matrix can be measured and evaluated.

A 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 enhancement of thermal conductivity is observed at high CNT loading for SWCNT (>5 % wt.), but it is very low in case of MWCNT (0.5%-1% wt.), as shown in Fig. 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-sized samples. The dispersion process with a suitable solvent like acetone 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 type of CNT, its amount in polymer and processing conditions.

CNT is an ideal nano-filler material to fabricate polymer composites but there are two major challenges: (1) uniform dispersion (2) adhesion between polymer and CNTs) which need to be addressed; some properties need to be studied before the realization of CNT-polymer nano-composites. 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 its impact on the process, in terms of influence upon the thermal and electrical properties of the composite; it is also helpful in analysing the effect of the amount of CNT dispersed 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.

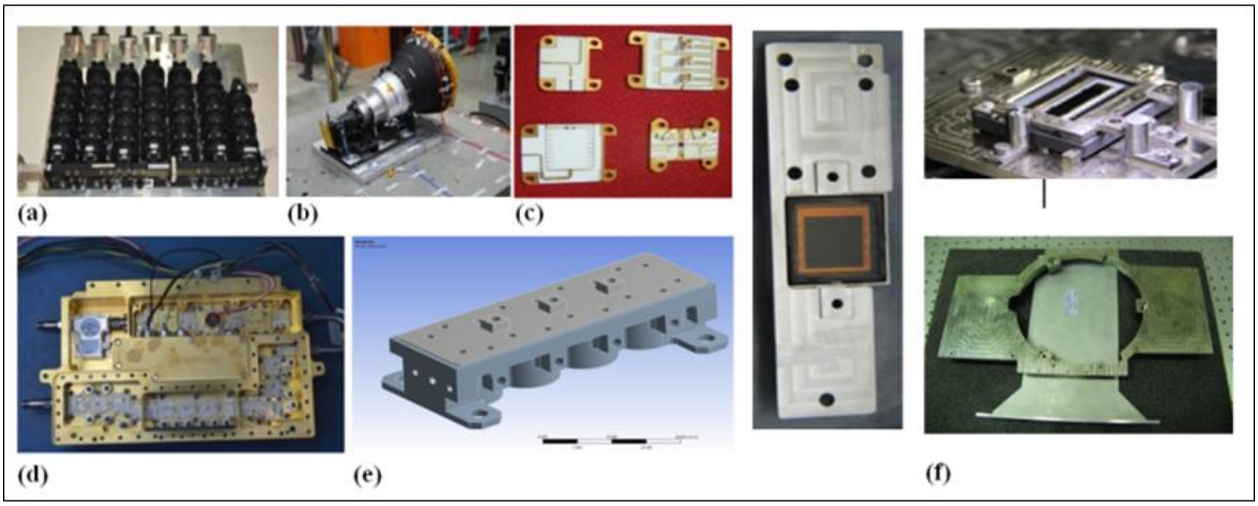

Fig. 9: a) Mux filter (b) Feed horn (c) Carrier plate (d) Electromechanical package (e) RF package and (f) Invar structures for optics

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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