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Real Time Defect Identification using Advanced Artificial Intelligence based Material Strain Sensors for Environmental Safety

***Abstract:* -** Advanced materials find applications in various fields of engineering and medicine. Many advanced materials are synthesized characterised to design sensors for various application including environmental protection. This work explores the possibility of real time defect identification using advanced materials such as graphene composite based sensor for Environment safety. Advanced materials like Graphene composite based sensor were prepared using solvent casting technique. Possibility of using graphene-PVDF based sensors as non- destructive probes to identify surface defects of materials were evaluated by probing on materials with pre-machined defects. Defects were induced artificially in different materials such as (SS316 LN stainless steel) flat plate and cylindrical disc plate. Defects vary both in size and depth. Nanocomposite films were cut in to small pieces of equal dimension and pasted over the various defects. The variation in size and depth of the defects is measured in terms of variation in resistance and suitably calibration graphs were obtained. Using advanced materials for environmental protection, Industry environment safety can be monitored and essential measures can be carried out. This work also explores the change in absorption property of carbon based nanocomposite films on addition of different weight percentage of advanced material based fillers such as Multiwalled carbon nanotubes and graphene. Filler weight percentage increases in matrix which is indicated by red shift in the absorption spectra.

In this research work the use of advanced materials for environmental protection in the Metallurgical Industry is explored . Development of advanced functional materials were carried out . Characterization of these advanced material were also carried out . Sensitivity of these advanced material based sensors were analyzed and calibarated. By using these advanced material based senors catastrophic disorders can be avoided and environmental safety is ensured.

The non-destructive evaluation (NDE) method that is being presented uses a Carbon Nanotube (CNT) and graphene-based sensor to identify defects in pre-machined stainless steel plates is innovative and straightforward. Utilizing nano composites is meant to combine the advantageous qualities of the filler and matrix. It was decided to use PVDF, a piezoelectric polymer, because of its benefits including low cost, versatility, and quick response time. A small amount (weight%) of MWCNTs and graphene are employed as filler to improve the material's shortcomings, such as delayed electrical response, and to make it behave as a piezoresistive and conductive material.

Keywords: Environmental protection; Carbon Nanotube; Sustainability.

I. INTRODUCTION

Advanced materials are to be used in designing of defect identification sensor to identify defects in engineering components[1]. In order to create graphene-based Nano composite films, several researchers [2] have suggested mixing graphene with other polymers. These films are used in a variety of industries, including electrical devices, energy storage, sensors, ESD, EMI shielding, as well as biomedical applications like cancer therapy, drug delivery, gene delivery, and other purported uses. It has been suggested that employing nanocomposite made of graphene oxide could improve mechanical properties including scratch resistance [3]. Researchers [4] took advantage of functionalized graphene sheets' potential for use with polymers (vinyl alcohol). Results demonstrate that functionalization gives compatibility with the polymer matrix and inhibits particle agglomeration. Graphene sheets aggression and random distribution of graphene sheets in composites are the major issues connected with dispersion of graphene in matrix[5]. Additionally, it was claimed that the near percolation ratio of the composites' electrical conductivity and dielectric constant increased by several orders of magnitude.

The primary goal of this research is to develop a nanomaterial-based sensor to identify surface defects in materials such as stainless steel, ferritic steel, carbon steel, and Zr alloy, among others. There are numerous non-destructive techniques available for failure analysis, structural integrity evaluations, health monitoring, and in-service inspection, including ultrasonic, eddycurrent, thermal imaging, radiography, phased array, and XRD residual stress[2][3]. The suggested work is a novel and straightforward non-destructive evaluation (NDE) method for identifying defects in stainless steel plates and turbine blades. Utilizing nano composites is meant to combine the advantageous qualities of the filler and matrix. It was decided to use PVDF, a piezoelectric polymer, because of its benefits including low cost, versatility, and quick response time. A little amount (weight%) of MWCNTs is added as filler in order to address its flaws, such as delayed electrical response, and make it behave as a piezoresistive and

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conductive material [5–6]. Materials and techniques, Results, Discussion, and finally Conclusion make up the paper's structure.

II. MATERIALS AND METHODS

Functionalized graphene/ Multiwalled carbon nanotubes and PVDF was dispersed in Di-Methyl- Formaldehyde (DMF)) and sonicated separately for 15 mins and then mixed together and sonicated for 15 mins. Magnetic stirring was carried out for 45 to 50 mins at 78°C to obtain homogeneous dispersion. Homogeneous solution obtained was poured on glass substrate and dried in an oven at 65°C for 10 hours in order to get solvent free films. Different weight percentage (2wt%, 3wt %, 4wt%, 6wt%, 8wt% and 10wt%) of graphene-PVDF films can be obtained by suitably mixing filler and matrix in required proportion[6-10].

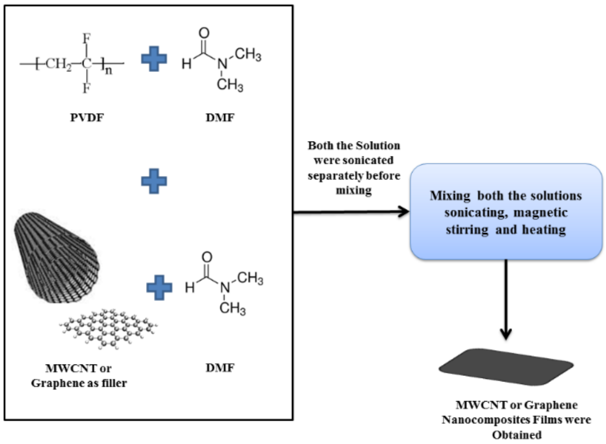

Figure 1: Schematic diagram representing preparation of Nanocomposite films

The sensor first needs to be calibrated to detect different sizes of defects. Graphene/ PVDF films are taken and are cut to equal sizes. These films are pasted on the defects induced regions using a nonconductive adhesive and probes are attached to both the ends of the film using silver epoxy and resistance variations in the films are tested at various location. Solvent casting is used to prepare multiwalled cabon nanotube and graphene based nanocomposite films [Siemann, 2005]. PVDF is the matrix. Filler can be changed depending on the type of nanocomposite films to be prepared. Schematic diagram representing preparation of nanocomposite films is shown in Figure 1.

Initial DMF dissolution of the filler and matrix is followed by 20 minutes of separate bath-style sonication of the filler and matrix. A magnetic stirrer is used to swirl the mixer for 45 minutes after the two solutions have been combined. Finally, nanocomposite films were created by drying the solution in an oven overnight at a temperature of 60 to 65 degrees. There are various precautions to be considered while preparation of both types of nanocomposite films. Sonication time need to be optimized in order to remove agglomerates of both fillers and polymers and to dissolve it completely in DMF solution. The duration of magnetic stirring is also critical to ensure that a homogeneous solution is obtained. Temperature maintained during magnetic stirring should not exceed permissible limit because prolonged duration of heating or heating at higher temperature will evaporate the DMF solvent present in the solution[11-17]. For proper evaporation the pettri dish should be kept open and care should be taken to ensure no impurities are present in the oven during formation of nanocomposite films.

Figure 1: UV-DRS Spectrometer

The device for ultraviolet-visible spectroscopy, also known as UV-Vis spectrophotometry (UV-Vis or UV/Vis), which relates to reflectance or absorption spectroscopy in the ultraviolet-visible spectral range, is depicted in Figure 1. It makes advantage of ultraviolet and nearby visible light spectrums. The colour of the compounds is directly impacted by the absorption or reflectance in the visible spectrum [Chandra et al., 2011]. In this portion of the electromagnetic spectrum, molecules go through electronic transitions. Numerous substances are capable of absorbing visible or ultraviolet light. Many compounds can absorb visible or ultraviolet light. Beer Lambert's Law states that A = bc, where b is the route length and c is the concentration of the adsorbing species. The absorptivity is a constant with the value of "". Molecules having n- or -electrons can absorb energy from ultraviolet or visible light to excite their electrons to higher anti-bonding atomic orbitals. The longer the wavelength of light it can absorb, the more readily excited the electrons are (i.e., the lower energy gap between the highest occupied and lowest unoccupied molar orbitals). The band gap energy can be calculated by, Band Gap Energy (E) = $\mathbf{hC}/\boldsymbol{\lambda}$, Where, h = Planks constant = 6.626 x 10^{-34} Joules sec, C = Speed of light = 3.0 x 10^{8} meters/sec, λ = Cut off wavelength = 410.57 x 10^{-9} meters where 1eV = 1.6 X 10^{-19} Joules (conversion factor)

III. RESULTS AND DISCUSSION

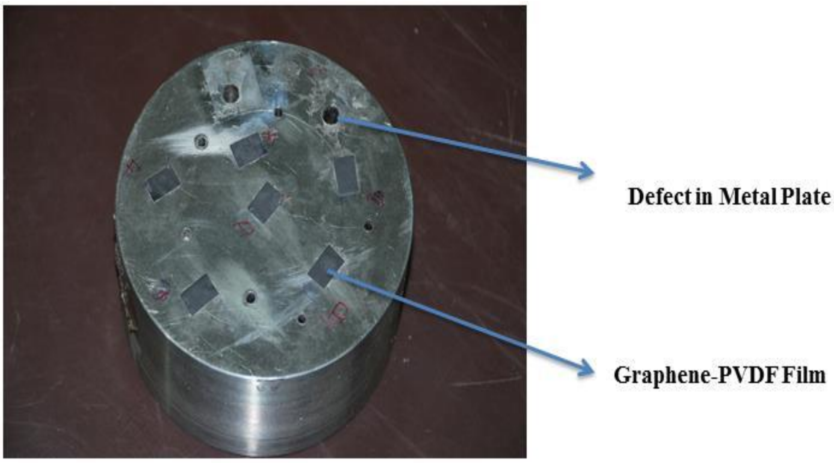

Figure 2: Cylindrical Metal Plate with varying Defect (both diameter and depth) Size

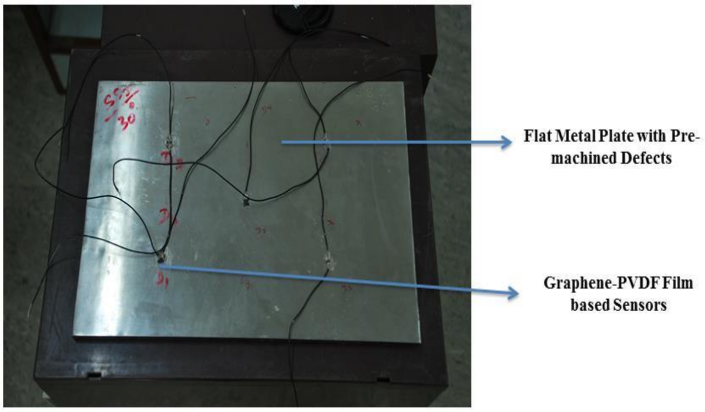

Figure 3: SS316 LN Flat Metal Plate with varying Surface Defects

Figure 2 shows cylindrical metal plate with varying defect size both in diameter and defect depth. Figure 3 shows flat metal plate with varying surface defects.

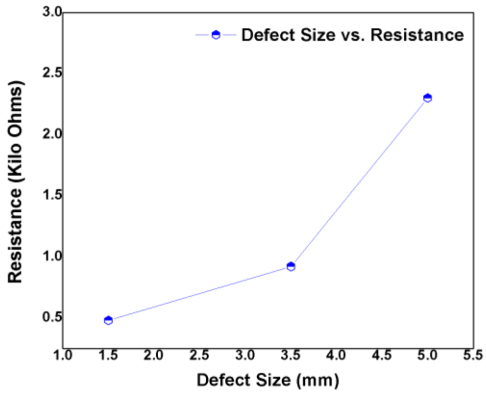

Figure 4: Defect Depth vs Resistance graph for Flat Metal Plate

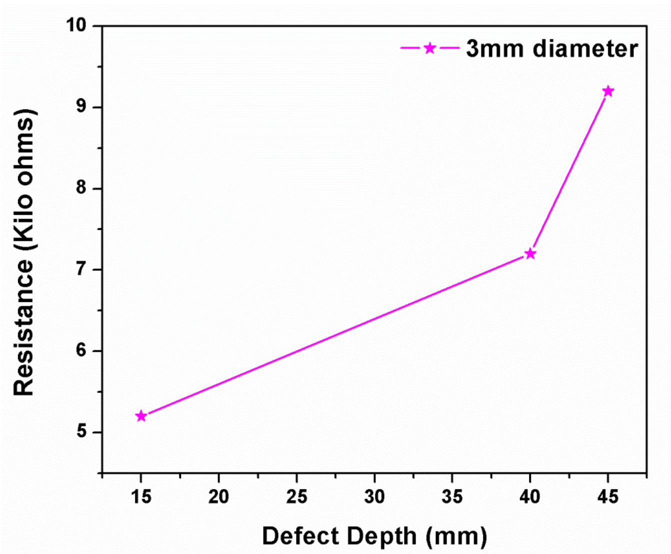

Figure 5: Defect Depth vs Resistance graph for 3mm diameter defect of Cylindrical Metal Plate

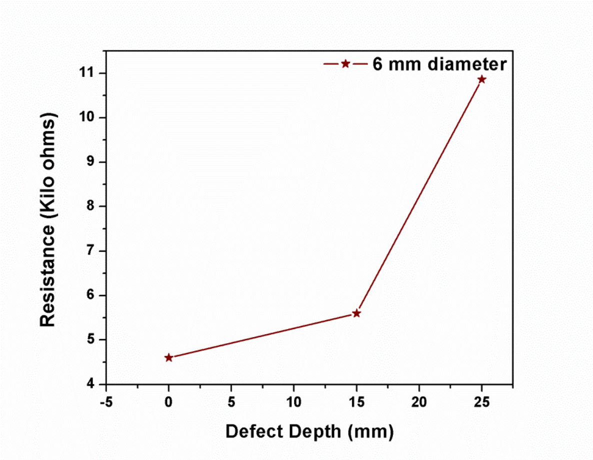

Figure 6: Defect Depth vs Resistance graph for 6mm diameter defect for Cylindrical Metal Plate

The developed graphene-PVDF films were cut into small pieces of equal dimensions and pasted over flat metal plate having pre-machined surface defect in the size ranging from 1.5 mm to 5 mm. As the defect size increases, the resistance value also increases from 0.5 kilo ohms to 2.3 Kilo ohms as shown in Figure 4. Defect measurements were also validated for cylindrical specimens with defects of varying depth and diameters. Defects of two different diameters, namely 3mm and 6mm, were machined on the surface of the cylindrical specimen. For 3 mm diameter as shown in Figure 5 there are 3 different depth size available namely 15 mm, 40 mm, 45 mm. Resistance of the sensor film varies as 5.2 K Ω, 7.2 K Ω and 9.2 K Ω over regions of the surface having defect depth of 15, 40 and 45 mm respectively.

Similarly for 6mm diameter as shown in Figure 6 there are 3 different depth size namely zero defect, 15 mm, 25 mm. The resistance of the sensor film pasted over the surface having above mentioned defect depth varied as 4.6 K Ω, 5.6 K Ω and 9.8 K Ω respectively. So from the obtained values, it is concluded that the resistance value changes for variation in defect size both surface (for increase in diameter size) and also for variation in defect depth. This technique is mainly used to identify the relative defect variation.

UV – DRS pattern of MWCNT/PVDF film is shown in Figure 7. The traced UV range for 3wt% is 368 nm whereas for 6wt% is 410 nm wavelengths. This shows that the red shift occurred in the nanocomposites due to the increasing weight percentage of MWCNTs which can be attributed to the electronic configuration of the carbon content. The Band gap Energy of the MWCNT nanocomposites is found to be E= $5.47\text{x}10^{-19}$ (J) and E_g = 3.41 (eV) for 3wt% and E = $4.88\text{x}10^{-19}$ (J) and E_g = 3.04 (eV) for 6wt% respectively . While increasing the weight percentage of MWCNT in nanocomposites, the density of states of MWCNT increases and forms a continuum of states just like in the bands and effectively the band gap decreases.

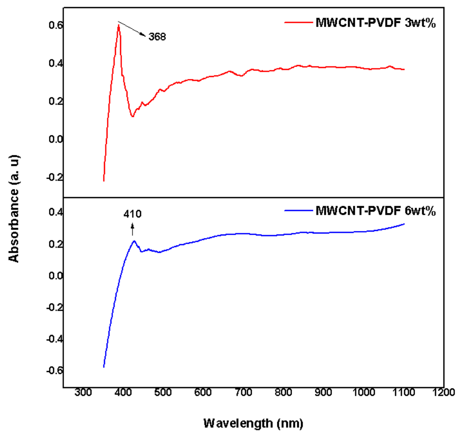

Figure 7: UV-DRS Spectrum of MWCNT nanocomposites

As the weight percentage of MWCNT increases in MWCNT-PVDF films, the number of π- electrons available will increase and it forms continuous band of electrons and hence there will be decrease in band gap. Due to decrease in band gap more number of free electrons is present in the highest occupied molecular orbits so it absorbs longer wavelength of light. So in the current work 6wt% MWCNT-PVDF films are absorbing higher wavelength compared to 3wt% MWCNT-PVDF films. Hence there is a red shift as the concentration of MWCNTs increases in PVDF matrix.

Figure 8 shows the UV – DRS pattern of f-graphene/PVDF film. The traced UV range for 2wt% is 363 nm and 375 nm whereas for 3wt% is 360 and 386 nm wavelength [Hu et al., 2014]. The other small peaks are also traced in the visible range as mentioned in the Figure 8

The Band gap Energy and Band gap of the graphene nanocomposites is found to be $E = 5.14 \times 10^{-19}$ (J) and E_g = 3.21 (eV) for 2wt% and $E = 4.45 \times 10^{-19}$ (J) and E_g = 2.81 (eV) for 3wt% respectively. While increasing the weight percentage of graphene in nanocomposites, the density of states of graphene increases and forms a continuum energy band and effectively reduces the band gap.

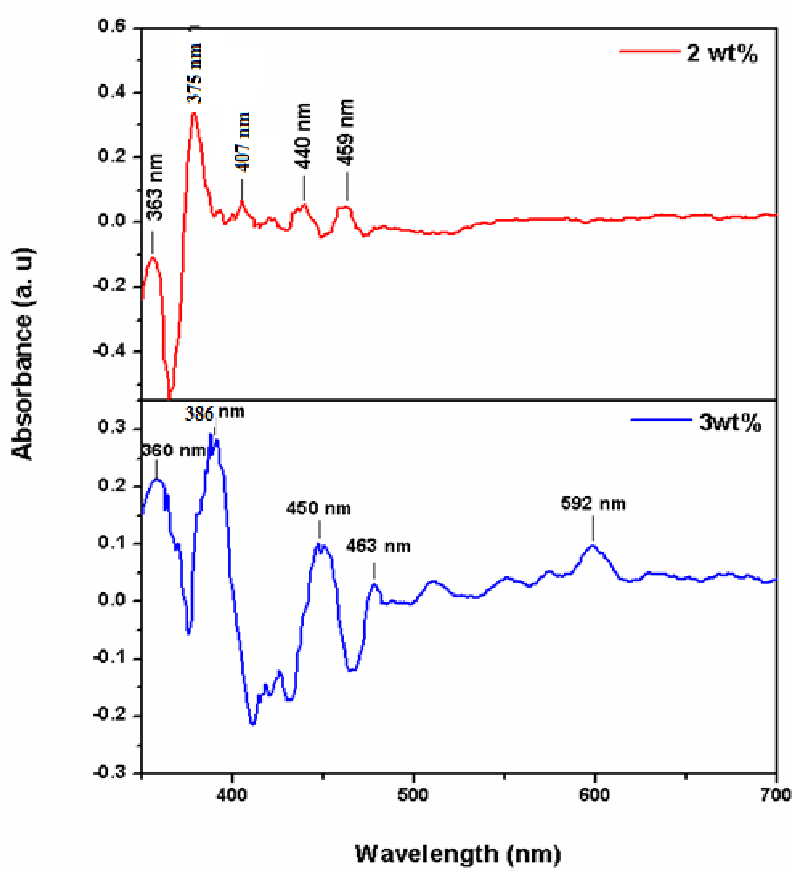

Figure 8: UV-DRS Spectrum of graphene-PVDF nanocomposites

As the weight percentage of graphene increases in graphene-PVDF films, the number of loosely bound electrons increases. These loosely bound electrons form continuous energy states and hence there will be decrease in the bandgap. Due to decrease in band gap more number of free electrons will be present in the highest occupied molecular orbits so it absorbs longer wavelength of light. So in the current work 3wt% graphene-PVDF films are absorbing higher wavelength compared to 2wt% graphene-PVDF films. Hence there is a red shift as the weight percentage of graphene increases in PVDF matrix.

IV. CONCLUSION

Advanced materials such as graphene and MWCNT based sensors can be used for environmental protection in Industrial sector. Defect Identification in pre-machined defect blocks were also calibrated as a function of resistance using Graphene-PVDF based sensors. Pre-calibrated defects were measured by noting the resistance variation for variation in defect size (both length and depth) by pasting the graphene-PVDF sensor film of equal dimension over the various defect sites. Calibration graph is drawn for defect variation as a function of resistance to identify unknown defect. Real time defect identification is possible using these technique in the future. These types of nanomaterial filled polymer films will find wide applications in making smart devices in near future. These sensors can be used for real time monitoring of components in metallurgical industries both during in-service and post service inspection.

Advanced material such as Graphene and MWCNT based polymer sensors can be used to detect defect initiation in automobiles subjected to heavy loading. Automobiles like buses, containers, trucks will be subjected to high stress during loading and unloading of goods. Hence, it is required to monitor such components continuously to evaluate the maximum load carrying capacity of critical components. The developed sensor will serve this purpose.

Chemical industries contain huge boilers and tanks, storing chemicals under aggressive conditions like high temperature/pressure. Formation of cracks can lead to leakage based catastrophic accidents. Continuous crack and strain monitoring of the boilers and containers is therefore required to avoid breakdown accidents. The newly developed advance material based sensor can be used for real time monitoring and alarming and thereby ensuring the safety of the industrial environment and also in turn the safety of human life.

In nuclear sector, reactor vessels are subjected to nuclear radiations and hazardous chemicals frequently. So there is a need to monitor its operation and structural integrity continuously. Structural health monitoring of these reactor components is possible by attaching the developed sensor to reactor vessel and other critical components.

Components in metallurgical industries are fabricated making use of different metals and alloys. Toughness, ductility and mechanical strength are very important parameters in design of components for engineering applications. The strain sensors being developed in the present work will be highly useful in finding the best fit for a particular application. This type of sensor also finds application in maintenance of bridges. Prolonged usage of constructed roads and bridges by vehicles will lead to initiation of cracks and pre-failure of these structures. By attaching these types of sensors one can possibly perform the real time structural monitoring of these roads and bridges. Cracks generated can be easily identified and precautions can be done before any damage. As the environmental factors such as pressure, temperature and weight composition of the materials changes the property of the composite film also expected to change. In the present research work, advanced material composition and filler concentration are changed and its impact is observed. In important engineering applications, early defect and strain detection might help prevent catastrophic mishaps. By generating a calibration curve that functions as a function of defect size and resistance, defect identification is achievable. This method can be used to detect strain and check flaws on engineering components in real time at crucial industrial locations. These types of advanced materials can be used as sensors to absorb the change in environment factors such as temperature, pressure etc.

Author credit Contributions

Deepak. A, - Conceptualization (Equal), Data curation (Equal), Investigation (Equal), Methodology (Equal), Validation and Writing (Equal) – original draft (Equal)

Yuvarajan Devarajan - Conceptualization (Equal), Validation (Equal) and Visualization (Equal)

Naveen. S- Funding acquisition (Equal), Investigation (Equal), Methodology and Supervision (Equal)

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study

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