Effects of functionalized carbon nanofillers on the spectral selectivity behavior of aluminum nanocomposites for solar absorber applications

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HIGHLIGHTS

- Spectral selectivity behavior of Aluminum (Al) based metal nanocomposites.
- Investigation of the MWCNT/MWCNTCOOH and GNP/GNPCOOH concentration on spectral and optical performances.
- Enhancing dispersibility of the nanofiller in Al with the addition of MWCNTCOOH/GNPCOOH nanofillers.

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ABSTRACT

The effects of functionalized multi-walled carbon nanotubes (MWCNTs) and graphene nanoplatelets (GNPs) on the spectral selectivity behavior of aluminum (Al) nanocomposites were investigated in this study. The attachment of the carboxylic (COOH) functional group on the surface of the carbon nanofillers was confirmed by Fourier transform infrared spectroscopy. The pristine and functionalized MWCNTs and GNP were introduced into pure Al powder at different concentrations (5, 10, and 15 wt%) to produce Al–MWCNT–GNP and Al–MWCNTCOOH–GNPCOOH nanocomposites. The results show that the dispersion of the carbon nanofillers is better and the spectral selectivity ratios are higher for the Al–MWCNTCOOH–GNPCOOH nanocomposites compared with those for Al–MWCNT–GPN nanocomposites. In addition, the light absorption is significantly enhanced in the ultraviolet, visible, and near-infrared regions (200–2500 nm) whereas the reflectance is significantly enhanced in the near-infrared, mid-infrared, and far-infrared regions (3000–14 000 nm) for the Al–MWCNTCOOH–GNPCOOH nanocomposites. The highest spectral selectivity ratio (27.41) is attained for the Al nanocomposite with 2.5 wt % MWCNTCOOH and 2.5 wt% of GNPCOOH.

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1. Introduction

Solar absorber is one of the key components of solar energy harvesting systems. Solar absorber needs to fulfill the following criteria: (1) high absorption in the ultraviolet (UV), visible (VIS), and near-infrared (NIR) of 200–2500 nm and (2) low emittance in the NIR, mid-infrared (MIR), and far-infrared (FIR) spectra within a wavelength range of 2500–16 000 nm in order to minimize thermal radiation losses, and (3) good thermal conductivity in order to maximize heat transfer to the exchange medium and maintain a stable operating temperature (>500 °C) [1,2]. It is known that high operating temperatures will lead to problems with the coatings used for solar absorbers. Sathiaraj et al. [3] and Tesfamichael et al. [4] conducted theoretical and experimental studies on the use of metal-dielectric composites such as nickel-pigmented aluminum oxide (Al2O3) as solar absorber coatings. However, such metal-dielectric composites degrade over long operating periods due to the oxidation of metal nanoparticles, especially in high-temperature and high-humidity environments [3,4]. At present, high-temperature paints such as Pyromark™ Series 2500 is the standard coating used for solar absorbers in concentrating solar power (CSP) systems. This paint has a high solar absorbance of 0.96 and more importantly, this paint is inexpensive and easy to apply. However, the thermal emittance of this paint is rather high (0.86),
which leads to large thermal losses during high-temperature operations [5]. In addition, the paint delaminates and degrades over time, which decreases the performance and increases the operating cost for solar absorbers [5]. The main problems of spectrally selective coatings are degradation and delamination of the coatings at high temperatures, inter-diffusion between layers, and oxidation since the coatings are exposed to air at high temperatures. All of these will degrade the performance of the solar absorber [5].

Spectrally selective coatings were originally developed with the intention to enhance the optical properties of the bulk materials. However, with technological advances over the years, it is not really accurate to say that spectrally selective coatings are merely developed to enhance the optical properties of the bulk materials. Nowadays, much effort is being made to develop thin films in addition to testing bulk and solid samples for spectrally selective applications. Even though bulk materials generally have better optical properties, these superior optical properties are achieved only for specific materials and operating conditions. According to Sani et al. [7], the optical properties of spectrally selective absorbers are different, depending on the materials used for the coatings. They fabricated spectrally selective absorbers from zirconium diboride (ZrB2) and tantalum diboride (TaB2) using a powder metallurgical process. The optimum TaB2 pellet was sintered through spark plasma sintering and reactive spark plasma sintering and the results showed that the TaB2 pellet has a solar absorbance of 0.40 and thermal emittance of 0.12 at 1400 K. In contrast, the ZrB2 pellet has a slightly higher solar absorbance of 0.47 at 1400 K, whereas the thermal emittance is the same as that for the TaB2 pellet.

In this study, it is believed that the dispersion of spectrally selective nanocomposites can be improved by incorporating carbon nanofillers (specifically multi-walled carbon nanotubes (MWCNTs) and graphene nanoplatelets (GNPs)) into aluminum (Al). Some of the findings obtained by the previous researchers [8–10] did report the excellent performance of both MWCNT and GNP nanofillers when incorporated together with base material such as metal and polymer. Al is one of the common base materials used for metal-MWCNT nanocomposites and metal-GNP nanocomposites due to its favorable thermal, optical, electrical, and mechanical properties and diverse range of technical applications [8,11–13]. In addition, Al is a lightweight material. The diameter of MWCNTs ranges from 1 nm to a few tens of nanometers and it has been reported that MWCNTs result in plasmon excitations [14], which improves the absorption of solar radiation [15]. Chen and Böstrom [16] investigated the use of MWCNTs in solar selective coatings and the results are indeed promising because the coatings have good spectral selectivity behavior, as indicated by high solar absorbance (>0.90%) and low thermal emittance (<0.15%). Meanwhile, graphene, which is a relatively new carbon material altered from the original structure of single-walled carbon nanotubes (SWCNTs), has garnered much attention from the scientific community because of its excellent thermal, mechanical, and electrical properties [17]. Unlike CNTs, graphene has a two-dimensional sheet-like structure with larger surface area, which makes it a good filler material for composites. In addition, it is relatively inexpensive to synthesize graphene [18].

It is believed that incorporating MWCNTs and GNP into the Al matrix will improve the optical properties of spectrally selective coatings. However, despite the unique properties of MWCNTs and GNP, both of these carbon nanofillers are prone to agglomeration during synthesis due to van der Waals forces between the particles. In addition, it is not possible to achieve effective interfacial bonding due to the poor affinity of MWCNTs and GNP toward Al. In order to address this issue, it is imperative to synthesize Al–MWCNT–GNP nanocomposites which fulfill the following criteria: (1) the MWCNTs and GNP should be uniformly dispersed within the Al matrix, and (2) there is sufficient interfacial bonding between the Al, MWCNTs, and GNPs [19]. This can be achieved by implementing a pre-treatment process in order to attach functional groups on the pristine MWCNTs and GNPs.

In this study, the spectral selectivity behavior of Al nanocomposites incorporated with functionalized MWCNTs and GNPs is investigated for the first time, to the best of the authors knowledge. The spectral selectivity behavior of the Al nanocomposites with functionalized MWCNTs and GNPs is compared with that pure Al and Al nanocomposites with pristine MWCNTs and GNPs. All of the samples are produced using the powder metallurgy technique. The effects of the functionalized MWCNTs and GNPs on the microstructure, and reflectance of Al nanocomposites are analyzed and discussed in detail in this paper. It is believed that the findings of this study will be of great interest to the scientific community to explore the potential of carbon nanofillers in enhancing the spectral selectivity behavior of spectrally selective absorbers.

2. Experimental procedure

2.1. Materials

Fig. 1 shows the image of as-received Al powder (brand: Acros Organics, purity: 99%, average particle size: 74 μm) purchased from Fisher Scientific (M) Sdn. Bhd., Malaysia, obtained from field-emission scanning electron microscopy (FESEM). Fig. 2(a) shows the FESEM image of the pristine MWCNTs (purity: 95%, outer diameter: 30–50 nm, length: 10–20 μm) whereas Fig. 2(b) shows the FESEM image of functionalized MWCNTs (MWCNTCOOH) after chemical treatment process. As shown in Fig. 2(a), the morphology of pristine MWCNTs is curly and intertwine with each other. The diameter of the pristine MWCNTs still maintain its uniform shape without any deformity on its structure. After the chemical treatment using combination of H2SO4/HNO3, the diameter of the MWCNTCOOH becomes a little smaller, due to the oxidation of the outer layer of MWCNTs by strong acid combination which can be seen in Fig. 2(b).

Fig. 3(a) shows the FESEM image of the pristine GNPs (average thickness: 2 nm, width: 1–2 μm, surface area: 300 m²/g) whereas Fig. 3(b) shows the FESEM image of functionalized GNPs (GNP-COOH) after chemical treatment process. The morphology of pristine GNPs shows a few layers of plane surface stack onto each other as shown in Fig. 3(a). After the chemical treatment using combination of H2SO4/HNO3, the plane surface of the GNP-COOH becomes a little smaller due to the oxidation of the outer layer of GNPs by strong acid combination which can be seen in Fig. 3(b). The pristine MWCNTs and pristine GNPs were purchased from XG Sciences, Inc., USA.

![Fig. 1. FESEM image of the as-received Al powder.](Image)
2.2. Preparation of the functionalized MWCNTs and GNPs

The MWCNTs and GNPs were functionalized using the following procedure. Firstly, 0.5 g of the as-received powder were added into a 20-mL mixture of sulfuric acid (18.37 M) and nitric acid (15.58 M), which was mixed at a volume ratio of 3:1. The mixture was stirred at 75°C for 2 h using a hot plate magnetic stirrer connected to a condenser in order to minimize evaporation of the acid. Next, the mixture was left to cool to room temperature (25–30°C) before it was diluted with a solution comprising 150 mL of distilled water and 50 mL of acetone. A bench-top centrifuge (Model: Rotofix 32A, Andreas Hettich GmbH & Co.KG, Germany) was used to separate the solids (functionalized MWCNTs and GNPs) from the mixture at 6000 rpm for 15 min. This step was carried out three times. The collected solids were washed with distilled water and then dried in a natural convection drying and heating chamber (Model: ED 23, BINDER GmbH, Germany) for 24 h at 80°C. The dried solids (in the form of film) were grounded into small particles prior to blending. The carboxylic (COOH) functional group was attached to the MWCNTs and GNPs during the blending process. Herein after, the functionalized MWCNTs and GNPs are represented by MWCNTCOOH and GNPCOOH, respectively, whereas the pristine MWCNTs and GNPs are represented by MWCNT and GNP, respectively.

2.3. Preparation of the Al, MWCNT, MWCNTCOOH, GNP, and GNPCOOH powders

To prepare the nanocomposites, the Al, MWCNT, MWCNTCOOH, GNP, and GNPCOOH powders need to be blended, ball-milled, cold-pressed, and sintered. The Al, MWCNT, MWCNTCOOH, GNP, and GNPCOOH powders were weighed and milled in zirconia jars with 32 g of zirconia balls (ball diameter: 5 mm, ball-to-powder ratio: 8:1) according to mixing ratios shown in Table 1. The ball milling process was carried out using a planetary ball mill (Model: PM 100, Retsch GmbH, Germany) at 400 rpm for 4 h with a break time of 5 min every 30 min. The break time is essential to prevent cold welding of the Al particles. Next, 8 mL of ethanol was added as a process control agent, which serves as a slurry mixing medium during the ball milling process. The milled powders were dried overnight at 80°C.

2.4. Compaction and sintering of the Al–MWCNT–GNP and Al–MWCNTCOOH–GNPCOOH nanocomposites

In this process, 2.5 g of the milled Al, MWCNT, MWCNTCOOH, GNP, and GNPCOOH powders were cold compacted in a die (diameter: 20 mm) at 300 MPa with a holding time of 20 min according to the mixing ratios shown in Table 1. After cold pressing, the pellets (diameter: 20 mm, thickness: 4 mm) were sintered at 625°C for 6 h in a tube furnace under constant flow of high-purity argon gas. The heating rate was set as 5°C/min. Pure Al pellet was also fabricated using the same procedure for comparison purposes. Herein, the Al nanocomposites with functionalized carbon nanofillers are denoted as Al–MWCNTCOOH–GNPCOOH nanocomposites whereas the Al nanocomposites with pristine carbon nanofillers are denoted as Al–MWCNT–GNP nanocomposites.

2.5. Characterization of the MWCNT, MWCNTCOOH, GNP and GNPCOOH powders

The attachment of the carboxylic (COOH) functional group onto the surface of the MWCNT and GNP nanofillers confirmed by Fourier transform infrared (FTIR) spectroscopy analysis. A FTIR spectrometer (Model: Nicolet iS50, Thermo Fisher Scientific, USA) was used for this purpose.

X-ray diffraction (XRD) analysis was carried out using an X-ray diffractometer (Model: X’pert PRO, Malvern Panalytical B.V., The Netherlands) to identify the crystalline phases of the pure Al sample, 85 wt% Al–7.5 wt% MWCNTCOOH–7.5 wt% GNPCOOH nanocomposite, and 85 wt% Al–7.5 wt% MWCNT–7.5 wt% GNP nanocomposite. The surface morphologies and distribution of carbon nanofillers of the pure Al sample, Al–MWCNTCOOH–GNPCOOH nanocomposites, and Al–MWCNT–GNP nanocomposites were examined using FESEM microscope (Model: AURIGA, Carl Zeiss Microscopy GmbH, Germany). The reflectance (R) of the samples was measured using UV–VIS–NIR spectrophotometer (Model: LAMBDA 750, Perkin Elmer, Inc., USA) within a wavelength range of 200–2500 nm. The reflectance of the samples was also measured using the FTIR spectrometer within a wavelength range of 3000–14 000 nm.

3. Results and discussion

3.1. FTIR spectroscopy analysis of the MWCNT, MWCNTCOOH, GNP, and GNPCOOH powders

FTIR spectroscopy was carried out to confirm the attachment of the carboxylic (COOH) functional group onto the surface of the pristine MWCNTs and GNPs after functionalization. The attachment of the functional group will improve the dispersibility of MWCNTs and GNPs in liquids, particularly water and ethanol, during the mixing process. Fig. 4 shows the FTIR spectra of the pristine and functionalized MWCNTs whereas Fig. 5 shows the FTIR spectra of the pristine and functionalized GNPs. It can be observed from the FTIR spectra for MWCNTCOOH and GNPCOOH that there are two distinctive peaks (O=H and C=O), which are due to the attachment of the COOH functional group onto the surface of the MWCNTs and GNPs. A new peak appears at 3436.29 cm⁻¹ for the MWCNTs after functionalization (Fig. 3) whereas the peak at 3435.04 cm⁻¹ broadens for the GNPs after functionalization (Fig. 4), which may be due to the presence of the hydroxyl group (O=H) stretching from the carboxyl groups (O=C=OH and C=OH) [20–22]. In addition, the presence of a new peak at 2925.24 cm⁻¹ [21] for the functionalized MWCNTs and the presence of a new peak at 2926.57 cm⁻¹ [21] and 1383.90 cm⁻¹ [8] for the functionalized GNPs are due to hydroxyl (O=H) stretching. Furthermore, a new peak appears at 1635.10 cm⁻¹ [23] and 1698.04 cm⁻¹ [22] for the functionalized MWCNTs, whereas a new peak appears at 1634.94 cm⁻¹ [24] and 1697.71 cm⁻¹ [22] for the functionalized GNPs, which are attributed to the stretching mode of the carboxylic groups. These results confirm the successful attachment of the carboxylic group (O=C=OH) onto the surface of the MWCNTs and GNPs.

3.2. XRD analysis of the pure Al sample and Al nanocomposites with 15 wt% of pristine and functionalized carbon nanofillers

Fig. 6 shows the X-ray diffractograms of the pure Al sample, Al
nanocomposite with 7.5 wt% MWCNTCOOH and 7.5 wt% GNPCOOH, and Al nanocomposite with 7.5 wt% MWCNT and 7.5 wt% GNP. It can be seen that there are four main peaks at 38.57° (111), 44.82° (200), 65.19° (220), and 78.73° (311) for the pure Al sample, which represent the structure of the Al particles. In contrast, a new peak is present at 26.6653° for both of the Al nanocomposites with pristine and functionalized carbon nanofillers. This peak indicates the presence of carbon, which is due to the addition of pristine and functionalized MWCNTs and GNPs [11,25]. It can be observed that there is no visible reflection peak from aluminum carbide (Al₄C₃) for the three samples. The peaks of Al₄C₃ (which are normally present at 31.8°, 55.0°, and 72.5°) are absent from the X-ray diffractograms [11], indicating that there is no appreciable reaction between the carbon nanofillers and Al during the blending and sintering processes. It is also evident that there are no significant changes in the intensity between the Al nanocomposites with pristine and functionalized carbon nanofillers, which indicates that the chemical treatment does not affect the original structure and integrity of the pristine GNPs and MWCNTs [26].

3.3. Surface morphologies of the pure Al sample, Al–MWCNT–GNP nanocomposites, and Al–MWCNTCOOH–GNPCOOH nanocomposites

3.3.1. Pure Al sample

The pure Al sample (100 wt% Al) was fabricated as a basis for comparison with Al nanocomposites containing different concentrations of carbon nanofillers. Fig. 7 shows the FESEM image of the pure Al sample which has been compacted and sintered into a pellet. It can be observed that there are micropores (as indicated by the black holes) in between the Al surfaces (indicated by the white color) due to the conventional sintering process adopted in this study. The micropores serve as light-trapping sites, which enhance light absorption. The presence of micropores also allow the carbon nanofillers to occupy these voids. The addition of carbon nanofillers such as MWCNTs and GNPs will further enhance the light absorption capability of the Al nanocomposite.

3.3.2. Al–MWCNT–GNP nanocomposites

Fig. 8 shows the surface morphologies of the Al nanocomposites with different concentrations of pristine MWCNTs and pristine GNPs. It can be observed from Fig. 8(a) and (b) that the pristine MWCNTs and GNPs are dispersed homogeneously in the Al nanocomposite with 2.5 wt% MWCNT and 2.5 wt% GNP and Al nanocomposite with 5.0 wt% MWCNT and 5.0 wt% GNP. It is evident from the images that the micropores are completely filled up with carbon nanofillers (as indicated by the black particles) while others are embedded within the Al surface. It is apparent from Fig. 8(c) that there is agglomeration of carbon nanofillers in the Al nanocomposite with 7.5 wt% MWCNT and 7.5 wt% GNP. This indicates that excessive amounts of carbon nanofillers result in stacking of the nanofillers, culminating in agglomeration. Interestingly, the dispersion of the carbon nanofillers is better in the Al
3.3. Al–MWCNT and Al–GNP nanocomposites

3.3.1. Al–MWCNT and Al–GNP nanocomposites

This work investigates the use of Al nanocomposites with 5 wt% MWCNT and 5 wt% GNP compared with the pristine carbon nanofillers. This effect is even more apparent for the Al nanocomposite with 5 wt% MWCNTCOOH and 5 wt% GNPCOOH (Fig. 9(b)) and Al nanocomposite with 7.5 wt% MWCNTCOOH and 7.5 wt% GNPCOOH (Fig. 9(c)). The results indicate that the COOH functional group improves the dispersibility of MWCNTs and GNPs in the Al matrix. In this study, it is found that the optimum concentration of carbon nanofillers is 5 wt% MWCNTCOOH and 5 wt% GNPCOOH since it is evident from the surface morphology of this sample that the functionalized carbon nanofillers are dispersed uniformly throughout the Al surface (indicated by the black spots).


The light reflectance (R) within a wavelength range of 200–2500 nm was measured using the UV–VIS–NIR spectrophotometer. Figs. 10 and 11 show the UV–VIS–NIR reflectance spectra of Al nanocomposites with different concentrations of pristine and functionalized carbon nanofillers, respectively. In general, there is a decrease in the reflectance with an increase in the concentration of carbon nanofillers. The reflectance is less than 40% for all Al nanocomposites, which is lower compared with that for the pure Al sample. This shows that the presence of carbon nanofillers improves the light absorption capability of Al nanocomposites [27,28].

It can be observed from Fig. 10 that the reflectance is low (<25%) within a wavelength range of 200–1000 nm and the reflectance increases at higher wavelengths for the Al–MWCNT–GNP nanocomposites, which is undesirable. However, the reflectance is reduced at higher wavelengths for the Al–MWCNTCOOH–GNPCOOH nanocomposites (Fig. 11), which indicates the advantage of incorporating functionalized carbon nanofillers.
The lower reflectance may be due to the more uniform dispersion of functionalized carbon nanofillers in the Al matrix, as evidenced from the FESEM images (Fig. 9). The UV–VIS–NIR reflectance values obtained in this study are superior to those of Sani et al. [29], who recorded a minimum reflectance of 30% at 200 nm for the hafnium carbide (HfC) sample with 20 wt% molybdenum disilicide (MoSi₂), which was sintered using the hot pressing method. The reflectance increased dramatically to 64% at 2500 nm. The results were similar for the zirconium carbide (ZrC) sample with 20 wt% MoSi₂, which was 39% at 200 nm, and the reflectance increased to 44% at 1000 nm and reached a maximum value of 66% at 2500 nm [29].

In order to examine the effect of attaching the COOH functional group onto the surface of MWCNTs and GNP, the UV–VIS–NIR reflectance spectra were grouped based on the concentration of carbon nanofillers in the Al nanocomposites, as shown in Figs. 12–14. It can be seen that there are two distinct wavelength ranges in the UV–VIS–NIR reflectance spectra: 200–1400 nm and 1400–2500 nm. In general, the reflectance is higher for the Al–MWCNTCOOH–GNPCOOH nanocomposites compared with that for the Al–MWCNT–GNP nanocomposites within a wavelength range of 200–1400 nm. However, the reflectance decreases with an increase in the concentration of functionalized carbon nanofillers. However, the reflectance is lower for the Al–MWCNTCOOH–GNPCOOH nanocomposites compared with that for the Al–MWCNT–GNP nanocomposites within a wavelength range of 1400–2500 nm. In this wavelength range, the reflectance also decreases with an increase in the concentration of functionalized carbon nanofillers.
functionalized carbon nanofillers. In addition, it can be observed that the UV–VIS–NIR reflectance spectra are almost coincident for the Al nanocomposites with 10 wt% of pristine and functionalized carbon nanofillers within a wavelength range of 1400–2500 nm. Based on the results, it can be deduced that the COOH functional group plays a significant role in reducing the light reflectance of Al nanocomposites.

3.5. FTIR spectroscopy analysis of the pure Al sample, Al–MWCNT–GNP nanocomposites, and Al–MWCNTCOOH–GNPCOOH nanocomposites

FTIR spectrometer was also used to measure the light reflectance of pure Al sample, Al–MWCNT–GNP nanocomposites, and Al–MWCNTCOOH–GNPCOOH nanocomposites within a wavelength range of 3000–14 000 nm and the results are shown in Figs. 15 and 16. The results obtained were also converted into emittance, which will be discussed in the next section. It can be seen from Fig. 15 that the Al nanocomposite with 2.5 wt% MWCNT and 2.5 wt% GNP has higher reflectance compared with the pure Al sample. The reflectance decreases with an increase in the concentration of pristine carbon nanofillers in the Al matrix. In contrast, all of the Al–MWCNTCOOH–GNPCOOH nanocomposites have higher reflectance compared with the pure Al sample, as shown in Fig. 16. The reflectance decreases with an increase in the concentration of functionalized carbon nanofillers; however, the reflectance is still
higher for the Al–MWCNTCOOH–GNPCOOH nanocomposites in the MIR and FIR regions compared with that for the pure Al sample. In order to examine the effects of attaching the COOH functional group onto the surface of the MWCNTs and GNPs within MIR and FIR regions, the FTIR reflectance spectra were grouped based on the concentration of the pristine and functionalized carbon nano fillers, as shown in Figs. 17–19. In general, it is apparent that the Al–MWCNTCOOH–GNPCOOH nanocomposites have higher reflectance compared with the Al–MWCNT–GNP nanocomposites. Even though the reflectance decreases with an increase in concentration of functionalized carbon nano fillers, the decrease in reflectance is not as marked as that for Al–MWCNT–GNP nanocomposites. The results indicate that the COOH functional group plays a vital role in retaining a high reflectance in the MIR and FIR regions for the Al nanocomposites.

The FTIR reflectance spectra obtained in this study are comparable to those of Sciti et al. [30] and Sani et al. [29]. Sciti et al. [30] found that the reflectance of the hafnium diboride (HfB2) pellet with 5 wt% MoSi2 was 88% at 3000 nm and the reflectance increased further to 99% at 14 000 nm [30]. The results were similar to those obtained by Sani et al. [29], who reported that the reflectance was 87% at 3000 nm for tantalum carbide (TaC) with 10 wt% MoSi2 and the reflectance gradually increased to 99% at 14 000 nm [29].

In general, the results obtained in this study are indeed encouraging because the Al–MWCNT–GNP nanocomposites and Al–MWCNTCOOH–GNPCOOH have lower reflectance within the UV, VIS, and NIR regions (200–2500 nm) and higher reflectance within the MIR and FIR regions (3000–14 000 nm). The results conform well with the behavior of an ideal solar absorber proposed.
by Kennedy [31], where solar absorbers should have low reflectance within the UV, VIS, and NIR regions (200–2500 nm) and higher reflectance within the NIR, MIR, and FIR regions (2500–25 000 nm).


Spectral selectivity is a key parameter which is used to improve the efficiency of solar absorbers [32]. The spectral selectivity behavior of a solar selective coating is represented by the absorbance-to-emittance ratio. Ideally, the light absorbance ($\alpha$) of the solar absorber should be high within the UV, VIS, and NIR regions (200–2500 nm) whereas the thermal emittance ($\varepsilon$) should be low within NIR, MIR, and FIR regions (2500–25 000 nm) [1,31].

Based on the reflectance spectra obtained from the UV–VIS–NIR spectroscopy measurements, the light absorbance ($\alpha$) of the pure Al sample, Al–MWCNT–GNP nanocomposites, and Al–MWCNTCOOH–GNPCOOH nanocomposites was determined from the following equation:
where \( \rho(\lambda) \) is the reflectance measured using the UV–VIS–NIR spectrophotometer, \( \lambda \) is the wavelength, and \( S(\lambda) \) is the sunlight spectrum. The limits of the definite integral are \( \lambda_{\text{min}} = 200 \text{ nm} \) and \( \lambda_{\text{max}} = 2500 \text{ nm} \).

Likewise, based on the reflectance spectra obtained from the FTIR measurements, the thermal emittance \( (\varepsilon) \) of the pure Al sample, \( \text{Al–MWCNT–GNP} \) nanocomposites, and \( \text{Al–MWCNTCOOH–GNPCOOH} \) nanocomposites was determined from the following equation:

\[
\varepsilon(T) = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{(1 - \rho(\lambda))B(\lambda)d\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} B(\lambda)d\lambda}
\]

where \( \rho(\lambda) \) is the reflectance measured using the FTIR spectrometer, \( B(\lambda) \) is the blackbody irradiance at a particular temperature, and \( \lambda \) is the wavelength. The limits of the definite integral are \( \lambda_{\text{m}} = 3000 \text{ nm} \) and \( \lambda_{\text{d}} = 14000 \text{ nm} \).

The spectral selectivity ratio \( (\xi) \) of the pure Al sample, \( \text{Al–MWCNT–GNP} \) nanocomposites, and \( \text{Al–MWCNTCOOH–GNPCOOH} \) nanocomposites was calculated by dividing the light absorbance \( (\alpha) \) with the thermal emittance \( (\varepsilon) \), as follows:

\[
\xi = \frac{\alpha}{\varepsilon}
\]

The light absorbance, thermal emittance, and selectivity ratios of the pure sample and Al nanocomposites are summarized in Table 2. In general, the additon of pristine and functionalized carbon nanofillers improve the spectral selectivity ratio of Al nanocomposites. It is evident that the \( \text{Al–MWCNTCOOH–GNPCOOH} \) nanocomposites have higher selectivity ratios compared with the \( \text{Al–MWCNT–GNP} \) nanocomposites.

The highest selectivity ratio (27.41) is attained for the Al nanocomposite with 2.5 wt% MWCNTCOOH and 2.5 wt% GNPCOOH, indicating that this is the optimum concentration of the functionalized carbon nanofillers. The light absorbance increases whereas the thermal emittance decreases with an increase in the concentration of pristine and functionalized carbon nanofillers. However, a different trend is observed for the Al nanocomposite with 7.5 wt% MWCNT and 7.5 wt% GNP since the thermal emittance is higher relative to that for pure Al, which results in lower spectral selectivity ratio.

In general, the spectral selectivity ratios obtained in this study are higher than those reported by other researchers for the same category of sintered materials. The highest spectral selectivity ratio obtained by Sani et al. \( [33] \) was 4.0 for TaB2 pellet sintered through spark plasma sintering. The highest spectral selectivity ratio obtained by Dan et al. \( [34] \) was 11.97 for W/WAIN/WAION/Al2O3 coatings produced using the electrodeposition process. Dudita et al. \( [35] \) synthesized a copper (II) oxide (\( \text{CuO} \)) and nickel (II) oxide (\( \text{NiO} \)) mixed film where 40 wt% of ethanol was deposited onto the copper substrate by spray pyrolysis. They obtained a spectral selectivity ratio of 36.4, which is 2.58 times higher than the highest spectral selectivity ratio obtained in this study.

### Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Light absorbance ( \alpha )</th>
<th>Thermal emittance ( \varepsilon )</th>
<th>Spectral selectivity ratio ( \xi )</th>
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<tbody>
<tr>
<td>100 wt% Al</td>
<td>0.56</td>
<td>0.23</td>
<td>2.43</td>
</tr>
<tr>
<td>95 wt% Al + 2.5 wt% MWCNT + 2.5 wt% GNP</td>
<td>0.80</td>
<td>0.15</td>
<td>5.33</td>
</tr>
<tr>
<td>95 wt% Al + 2.5 wt% MWCNTCOOH + 2.5 wt% GNPCOOH</td>
<td>0.73</td>
<td>0.03</td>
<td>27.41</td>
</tr>
<tr>
<td>90 wt% Al + 5 wt% MWCNT + 5 wt% GNP</td>
<td>0.84</td>
<td>0.21</td>
<td>4.00</td>
</tr>
<tr>
<td>90 wt% Al + 5 wt% MWCNTCOOH + 5 wt% GNPCOOH</td>
<td>0.79</td>
<td>0.11</td>
<td>7.18</td>
</tr>
<tr>
<td>85 wt% Al + 7.5 wt% MWCNT + 7.5 wt% GNP</td>
<td>0.86</td>
<td>0.38</td>
<td>2.26</td>
</tr>
<tr>
<td>85 wt% Al + 7.5 wt% MWCNTCOOH + 7.5 wt% GNPCOOH</td>
<td>0.82</td>
<td>0.15</td>
<td>5.47</td>
</tr>
</tbody>
</table>

4. Conclusion

The effects of functionalized carbon nanofillers on the spectral selectivity behavior of Al nanocomposites was investigated in this study in order to assess the potential of these nanocomposites for solar absorber applications. The \( \text{Al–MWCNT–GNP} \) and \( \text{Al–MWCNTCOOH–GNPCOOH} \) nanocomposites were prepared by chemical treatment, and FESEM imaging and UV–VIS–NIR and FTIR spectroscopy measurements were carried out to characterize the samples. The results show that the homogeneous dispersion of MWCNTCOOH and GNPCOOH in the Al matrix increases the light absorbance within a wavelength range 200–2500 nm and decreases the thermal emittance within a wavelength range 3000–14000 nm. The spectral selectivity ratios of the \( \text{Al–MWCNTCOOH–GNPCOOH} \) nanocomposites are higher compared with those for the \( \text{Al–MWCNT–GNP} \) nanocomposites and pure Al sample. The highest spectral selectivity ratio (27.41) is achieved for the Al nanocomposite with 2.5 wt% MWCNTCOOH and 2.5 wt% GNPCOOH. The high spectral selectivity ratio indicates the great potential of this nanocomposite as a spectrally selective material for solar absorber applications.

Acknowledgment

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References

[6] A. Rouault, et al., Accelerated aging of a solar absorber material subjected to...


