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Silane functionalization of WS₂ nanotubes for interaction with poly(lactic acid)[†]

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Functionalisation of nanofillers is required for the promotion of strong interfacial interactions with polymers and is essential as a route for the preparation of (nano)composites with superior mechanical properties. Tungsten disulphide nanotubes (WS₂ NTs) were functionalized using (3-aminopropyl) triethoxysilane (APTES) for preparation of composites with poly(lactic acid) (PLA). The WS₂ NTs : APTES ratios used were 1 : 1, 1 : 2 and 1 : 4 WS₂ NTs : APTES. The APTES formed siloxane networks bound to the NTs *via* surface oxygen and carbon moieties adsorbed on the WS₂ NTs surface, detected by X-ray photoelectron spectroscopy (XPS) studies and chemical mapping using energy dispersive X-ray spectroscopy in the scanning transmission electron microscope (STEM-EDS). The successful silane modification of the WS₂ NTs was clearly evident with both significant peak shifting by as much as 60 cm⁻¹ for Si–O–Si vibrations (FTIR) and peak broadening of the A_{1g} band in the Raman spectra of the WS₂ NTs. The evolution of new bands was also observed and are associated with Si–CH₂–CH₂ and, symmetric and asymmetric –NH³⁺ deformation modes (FTIR). Further evidence for functionalization was obtained from zeta potential measurements as there was a change in surface charge from negative for pure WS₂ NTs to positive for APTES modified WS₂ NTs. Additionally, the thermal stability of APTES was shifted to much higher temperatures as it was bound to the WS₂ NTs. The APTES modified WS₂ NTs were organophilic and readily dispersed in PLA, while presence of the pendant amine and hydroxyl groups resulted in strong interfacial interactions with the polymer matrix. The inclusion of as little as 0.5 wt% WS₂ NTs modified with 2.0 wt% APTES resulted in an increase of 600% in both the elongation at break (a measure of ductility) and the tensile toughness relative to neat PLA, without impacting the stiffness or strength of the polymer.

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1. Introduction

Tungsten disulphide nanotubes (WS₂ NTs) continue to attract increased attention given their interesting and useful properties including, mechanical^{1,2} (*e.g.* Young's modulus of 170 GPa and tensile strength of 16–20 GPa), and electrical and optical behaviour.^{3–7} Furthermore, they have been shown to have non-toxic and biocompatible properties.^{8–10} As with most 0D/1D/2D materials, there is a great interest in translating some of these properties to polymer matrices to enhance

chemical and physical properties *via* effective dispersion and distribution of the NTs throughout the polymer matrix. The 1D structure of WS₂ NTs is co-centric molecular cylinders consisting of a rolled plane of W atoms sandwiched between two rolled planes of S atoms and kept together by strong covalent bonds, while the molecular S–W–S layers (cylinders) are bonded by weak van der Waals forces.¹¹ Weak interactions between neighbouring NTs can result in agglomeration and the formation of NT bundles. This can pose a significant technical challenge with regards to homogenous dispersion and distribution of the NTs within polymer matrices, which, if not achieved, often results in poor material properties.¹² Additionally, achieving well dispersed nanofillers relies also on the extent of interfacial interactions between the polymer matrix and the nanofiller, which is highly dependent on the surface chemistry of each material. Surface modification of inorganic nanoparticles with silane coupling agents can produce and aid dispersion and promote enhanced interfacial interactions between the nanoparticles and the polymer matrices.^{12–19} Examples include (3-aminopropyl)triethoxysilane (APTES) functionalization successfully grafted *via* a hydro-

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lysis mechanism on the surface of nanoparticles.^{15,20–24} Silane surface functionalisation of WS₂ NTs has not been widely investigated, with a few exceptions, and limited to where the matrix is an epoxy (see however ref. 25) or for other applications. Shahar *et al.* were the first to functionalize the surface of WS₂ fullerene-like nanoparticles with organo-silane molecules and reported better dispersion in oil-based suspensions.²⁶ While Sade *et al.* studied the functionalisation of WS₂ NTs with both conformal humin-like coatings and APTES,²⁷ the authors confirmed successful attachment of APTES to the surface of the NTs. Critically, the functional amine group of APTES is then available for further interaction with polymers.

Poly(lactic acid) (PLA) is a biodegradable thermoplastic of interest in biomedical and biopolymer materials research, with applications as diverse as tissue engineering, cardiovascular implants, dental niches, drug carriers, orthopaedic engineering, cancer therapy, skin and tendon healing, and in medical tools and equipment.^{28–37} However, PLA, depending on the D- and L-isomer content can have poor properties including a high degree of brittleness and low gas barrier properties.³⁸ Consequently, given the excellent combination of WS₂ NT mechanical and biocompatible properties, reinforcement of PLA for Bioresorbable Vascular Scaffolds (BVS)^{39,40} and bone tissue engineering^{41,42} are of great interest. WS₂ NTs have already been shown to readily dispersible in PLA and at loadings as low as 0.5 wt% increase the elastic modulus, yield strength and strain-at-failure of the polymer by 20%, 23% and 35%, respectively.⁴³ This behaviour is attributed to effective NT dispersion and the nucleating effect the NTs have on the PLA which in turn has a significant effect on PLA crystalline content.^{44–48} Interestingly, in another study, inclusion of these NTs was reported to have had a plasticising effect on the polymer.⁴⁰

In this paper, we report for the first time the functionalisation of WS₂ NTs with APTES and their use as a functional filler for PLA. The effectiveness of the silane grafting to the surface of NTs is investigated as an approach to enhance NT dispersion in the polymer matrix and promote strong interfacial interaction between the WS₂ NTs and PLA as a route for improving the mechanical properties of PLA.

2. Experimental

2.1 Materials

Details of the synthesis and characterization of the WS₂ NTs is described in ref. 49. Briefly, the NTs were synthesized *via* vapor-gas-solid (VGS) high-temperature reaction between tungsten oxide and reactive gases, such as hydrogen sulfide and hydrogen, using nitrogen as carrier gas, custom made quartz reactor with specially designed porous reaction cell and one-zone horizontal split furnace.⁴⁹ Poly(L-lactic acid) (PLA) was supplied by Corbion Luminy® LX17 consisting of at least 96% L-isomer. (3-Aminopropyl)triethoxysilane (APTES, 98%) and Dichloromethane (DCM, 99.8%) were purchased from Sigma Aldrich and used as received.

2.2 Preparation of APTES modified WS₂ NTs

0.25 g of WS₂ NTs were dispersed in 30 ml dichloromethane (DCM) by ultrasonic bath treatment (3 minutes). The APTES was added to this solution in ratios of 1:1 (0.25 g WS₂:0.2643 ml APTES), 1:2 (0.25 g WS₂:0.5285 ml APTES) and 1:4 (0.25 g WS₂:1.057 ml APTES), the density of APTES is 0.946 g ml⁻¹. The APTES:WS₂ NTs DCM solutions were then mechanically stirred at 500 rpm overnight at room temperature. The silane modified WS₂ NTs were dried at room temperature (RT) for 8 hours followed by drying at 40 °C under vacuum for 12 hours.

2.3 Preparation of composites of APTES:WS₂ NTs and PLA

Composites of APTES modified WS₂ NTs were prepared *via* solution mixing and solvent casting. Firstly, 0.5 wt% WS₂ NTs (0.05 g) were fully dispersed in 30 ml of DCM assisted using ultrasonic bath treatment (3 min) and then 0.5, 1.0 and 2.0 wt% APTES (0.05 g/0.0526 ml, 0.1 g/0.1057 ml, 0.2 g/0.211 ml respectively, for different NTs:APTES ratios) was added, followed by stirring overnight to allow the completion of the reaction. Second, PLA (10 g) was dissolved in 50 mL of DCM under magnetic stirring in a 250 mL round-bottom flask at RT. Once prepared, APTES:WS₂ NTs DCM solutions were added to the PLA-DCM solution and mechanically stirred overnight at 500 rpm. The resulting solutions were cast in Petri dishes and dried at RT for 8 h followed by drying at 40 °C under vacuum for 12 h to produce composites of PLA with APTES modified WS₂ NTs in a film form. These films were then hot pressed using a Collin Hot Press (P 200 PM) at 190 °C in a mould for 4 min and cooled to RT at a rate of 10 K min⁻¹ to obtain the final film with a thickness of ~0.5 mm.

2.4 Characterisation

Fourier transform infrared (FTIR) spectra were collected in transmission mode using a Bruker Tensor 27 FTIR spectrometer. Measurements were recorded in the wavenumber range 500 cm⁻¹–4000 cm⁻¹ with a resolution of 2 cm⁻¹ and 16 scans were accumulated.

Thermogravimetric analysis (TGA) was carried out using a Mettler Toledo instrument, using alumina pans, in the temperature range 25 °C to 1000 °C at a heating rate of 10 K min⁻¹ under a nitrogen atmosphere.

X-ray photoelectron spectroscopy (XPS) measurements were carried out using a Kratos Axis Ultra DLD spectrometer (Kratos Analytical, Manchester, UK). Samples were mounted on electrically conductive carbon tape upon the sample bar and loaded into the spectrometer. Once a pressure better than 1 × 10⁻⁶ mbar had been reached, the samples were transferred to the main analysis chamber. The samples were illuminated by a mono-chromated Al K α X-ray source ($h\nu = 1486.7$ eV) and flooded with low energy electrons from a charge neutraliser in order to prevent the surface from becoming positively charged during the experiment. Data were collected at a take-off angle of 90° in a hemispherical analyser using a pass energy of 160 eV for survey spectra and 20 eV for high resolution core level spectra (resolution approx. 0.4 eV). Data were analysed by the CasaXPS software package, using mixed Gaussian-Lorentzian



(Voigt) line-shapes and Shirley backgrounds. The spectrometer was calibrated with the Ag 3d_{5/2} peak and Fermi edge of clean polycrystalline Ag prior to the start of the experiments, with the transmission function determined by various clean metallic foils. The binding energy scale was calibrated during the analysis, with the C–C/C–H component in the C 1s region at 285.0 eV as the reference point.

The Raman spectra of neat WS₂ NTs and APTES functionalised NTs were collected on a Renishaw Invia spectrometer fitted with a 633 nm laser. They were recorded under ambient conditions with a 50× magnification objective using 5% of laser power (0.5 mW) spot focused on the sample with an exposure time of 10 seconds and up to 1600 accumulations.

Scanning electron microscopy (SEM) images were obtained on a Zeiss Sigma field emission instrument using an operating voltage of 3 kV. WS₂ NTs and APTES modified WS₂ NTs were carefully deposited onto double-sided conductive carbon adhesive tape on an SEM stub. The composites of APTES functionalised WS₂ NTs and PLA were cryo-fractured and also placed on adhesive carbon tape and the fractured surfaces examined. All samples were sputter coated with a ~20 nm thick film of carbon using a Safematic CCU-010 Compact Coating Unit. Scanning Transmission Electron Microscopy (STEM) imaging of the NTs was carried out using a FEI (Thermo Fisher Scientific) Talos F200X microscope, operating at 200 kV throughout the analysis. The microscope had a X-FEG (Field Emission Gun) high-brightness electron source and was fitted with a Super-X EDS (Energy Dispersive X-ray Spectroscopy) system with integrated four silicon drift detectors, providing a solid angle of 0.9 sr for rapid chemical composition mapping. Samples were prepared by dispersion in methanol and transferred on to holey carbon coated grids. The data were acquired using either FEI TIA™ or Velox™ software, and both High-Angle Annular Dark-Field (HAADF) images and Bright-Field (BF) images were taken simultaneously.

Zeta potential measurements were conducted on all samples diluted with 0.5 ml methanol and vigorously shaken to ensure good dispersion before being loaded into an Omega zeta potential cuvette. Samples were run in triplicate for 100 runs at 25 °C.

Tensile mechanical testing was performed using an Instron 5800R instrument operating Bluehill 2 software. 5–7 dog bone shaped specimens were prepared and tested for each composite. Tests were carried out with a video extensometer using a constant crosshead speed of 1 mm min⁻¹.

DSC measurements were carried out using a Mettler Toledo DSC 1 under a nitrogen atmosphere, a heating rate of 10 K min⁻¹ from 25 to 200 °C, isotherm at 200 °C for 2 minutes and cooled at 10 K min⁻¹ from 200 to 25 °C. The percentage crystallinity (*X_c*) of the samples was calculated using the following eqn (1):

$$\left(\frac{\Delta H_m - \Delta H_{cc}}{\omega \Delta H_m^0} \right) \times 100 \quad (1)$$

where, ΔH_m , ΔH_{cc} are the enthalpy of melting and cold crystallisation, respectively, ω is the weight fraction of PLA in each com-

posite, and ΔH_m^0 is the melting enthalpy of a theoretically 100% crystalline PLA which has been reported to be 93.7 J g⁻¹.⁵⁰

3. Results and discussion

To determine if APTES functionalisation of the NTs was successful, the FTIR spectra of WS₂ NTs: APTES in the ratios 1 : 1, 1 : 2 and 1 : 4 in comparison with the spectra for WS₂ NTs and APTES alone were recorded (Fig. 1). The FTIR spectrum of WS₂ NTs does not display any peaks in the infrared due to the WS₂ having no dipole moment as a result of its symmetry modification which causes a change in polarizability.⁵¹ A consequence of being rolled into 1D multiwalled nanotubes is a loss of symmetry and the WS₂ becomes an asymmetrical crystal. This results in WS₂ NTs having new properties, including displaying a bulk photovoltaic effect, piezoelectricity and ferroelectricity.^{49,52,53} APTES displays characteristic peaks at 3383 cm⁻¹ and 2974 cm⁻¹ which are related to amine NH₂ stretching. Peaks at 1604 cm⁻¹ and 1483 cm⁻¹ and related peaks are assigned to NH₂ deformation bending modes of amine groups, which are strongly bonded in the hydrogen to the silanol groups to form cyclic structures.⁵⁴ Peaks at 1442 cm⁻¹ and 1390 cm⁻¹ correlate to O–H bending, while those at 1294 cm⁻¹ and 1165 cm⁻¹ are associated with C–O stretching of the aromatic ester. Asymmetric and symmetric Si–O–Si vibrations were recorded at 1073 cm⁻¹ and 765 cm⁻¹, as well as a Si–O–C asymmetric peak at 1100 cm⁻¹.⁵⁵ Si–OH stretching and bending vibrations are observed at 954 cm⁻¹ and 853 cm⁻¹, respectively.⁵⁶ The peak at 677 cm⁻¹ is associated with N–H bending.

For the APTES functionalized WS₂ NTs at all ratios (Fig. 1(b)), similar FTIR transmittance spectra were obtained, and with increasing silane content the intensity of all peaks increases monotonically, suggesting successful grafting of the silane moiety to the NT surface. The spectra for APTES modified WS₂ NTs shows a shift of the N–H stretching vibrations with respect to neat APTES from 3383 cm⁻¹ and 2974 cm⁻¹ to 3348 cm⁻¹ and 3270 cm⁻¹, which are superimposed on a broad peak in the 3500–2500 cm⁻¹ region associated with O–H stretching mode as a result of water absorption in the sample. However, the evolution of new bands is identified and depicted in Fig. 1(c), the one at 1570 cm⁻¹ is assigned to the asymmetric –NH₃⁺ deformation mode, with the corresponding symmetric –NH₃⁺ mode at 1470 cm⁻¹.²¹ The band at 1305 cm⁻¹ is characteristic of C–N stretching in amines, while Si–CH₂–R vibrational modes are typically observed in the range 1250–1200 cm⁻¹,⁵⁷ therefore the band at 1232 cm⁻¹ is associated with Si–CH₂–CH₂. An O–H band is observed again for the functionalized NTs but is shifted to 1383 cm⁻¹. For APTES modified WS₂ NTs, there is a shift of all peaks in the region 1150–600 cm⁻¹ (Fig. 1(d)) relative to pure APTES. The symmetric Si–O–Si vibrations are red-shifted by 61 cm⁻¹ from 1073 cm⁻¹ (APTES) to 1012 cm⁻¹ when grafted on to WS₂ NTs in the ratio of 1 : 1. A further shift of 7 cm⁻¹ to 1005 cm⁻¹ is observed for the WS₂ NTs: APTES 1 : 2 sample, and again a



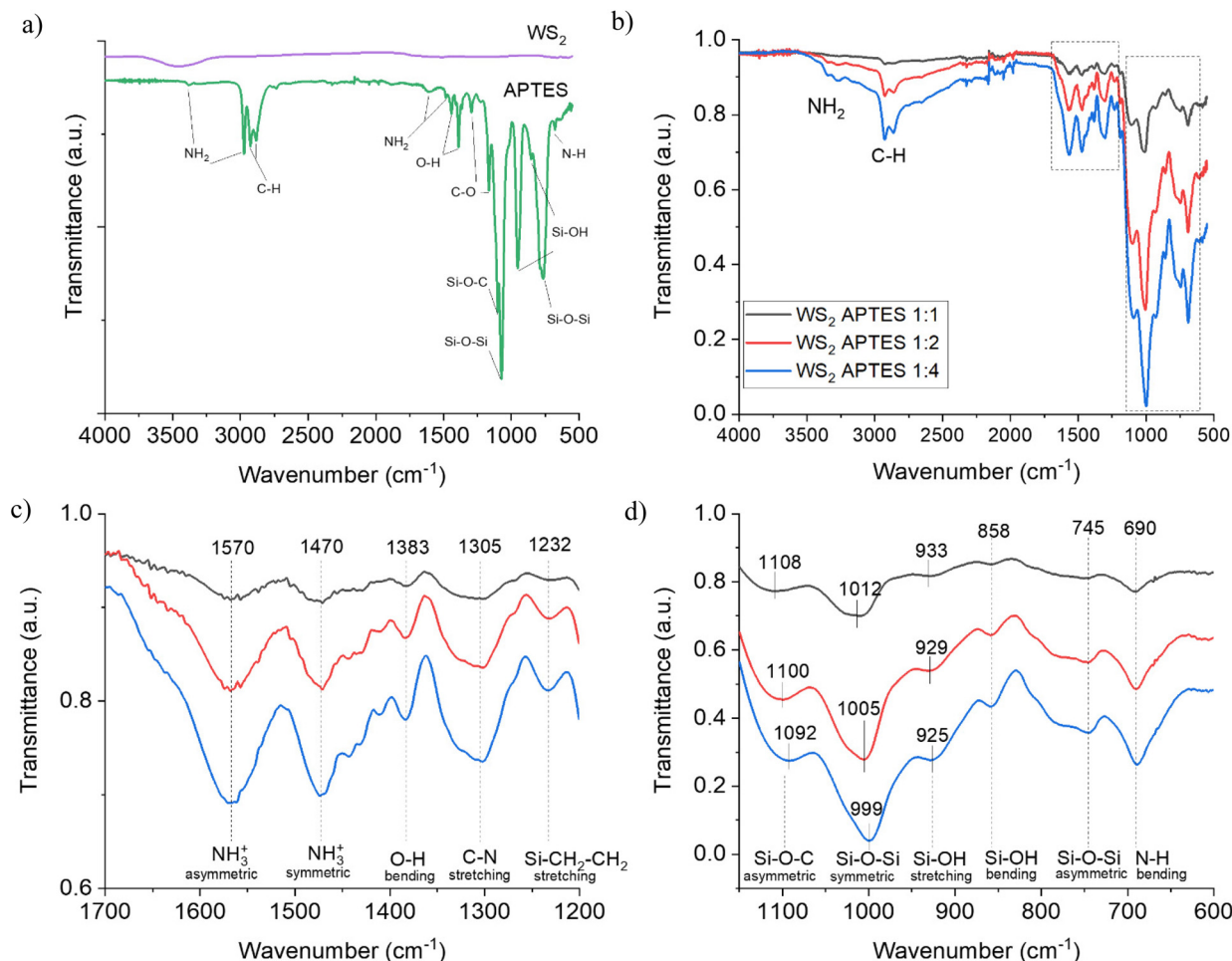


Fig. 1 FTIR transmittance spectra of, (a) WS₂ NTs and APTES, (b) APTES functionalized WS₂ NTs in ratios of 1 : 1, 1 : 2 and 1 : 4, (c) spectra enlarged in the range 1700–1200 cm⁻¹ and (d) in the range 1150–600 cm⁻¹.

shift of a further 7 cm⁻¹ to 998 cm⁻¹ for WS₂ NTs : APTES 1 : 4. The asymmetric Si–O–Si vibration band is observed at the lower (relative to the symmetric Si–O–Si vibration) wavenumber of 745 cm⁻¹ irrespective of the ratio of WS₂ NTs to APTES. There was also a variation in the peak shift of band position for the asymmetric Si–O–C from 1100 cm⁻¹ for APTES to 1108 cm⁻¹, 1100 cm⁻¹ and 1092 cm⁻¹ for 1 : 1, 1 : 2, 1 : 4 WS₂ NTs : APTES, respectively. Si–OH stretching and bending vibrations are observed at 929 cm⁻¹, 858 cm⁻¹ and 780 cm⁻¹, respectively.⁵⁶ Furthermore, the N–H bending peak blue shifts by 13 cm⁻¹ to 690 cm⁻¹ after the surface modification of the WS₂ NTs. These new bands, observed for APTES modified WS₂ NTs in comparison to APTES alone and shifting of the peaks with increased ratio of APTES, provides evidence for the formation of a siloxane network on the surface of the WS₂ NTs, confirming strong interaction of APTES with the surface of the NTs.

The effectiveness of surface functionalization of the WS₂ NTs with APTES was also investigated by studying the thermal stability of the surface modified NTs using thermogravimetric analysis under N₂ atmosphere, Fig. 2. The onset of thermal

degradation of APTES alone (even under a non-oxidative atmosphere) was just above ambient temperature with a 90% mass loss by 200 °C. In contrast, the WS₂ NTs are shown to be thermally stable across the whole temperature range (25 °C–1000 °C) examined with a total weight loss of just 2.5%. When bound to the WS₂ NTs the thermal decomposition profile of APTES is shifted to higher temperatures with weight losses of 32.1%, 32.9% and 36.4%, for WS₂ NT : APTES in the ratios 1 : 1, 1 : 2 and 1 : 4, respectively. This increase in mass loss with increasing APTES concentration further supports the idea that the APTES is bound to the WS₂ NTs. Additionally, the DTG curves for the APTES modified WS₂ NTs (Fig. 2(b)) show that, irrespective of the APTES concentration the weight loss occurs in three main stages. Below 100 °C, mass loss is attributed to the removal of water from the surface of the NTs. A second small peak with maxima at ~329 °C for the 1 : 1 and 1 : 2 sample, increasing to 354 °C for the 1 : 4 sample, is associated possibly with the removal of residual surfactant. Above 400 °C a third peak with maxima at 500 °C is observed perhaps derived from the decomposition of the functional groups chemically anchored to the surface of NTs given the



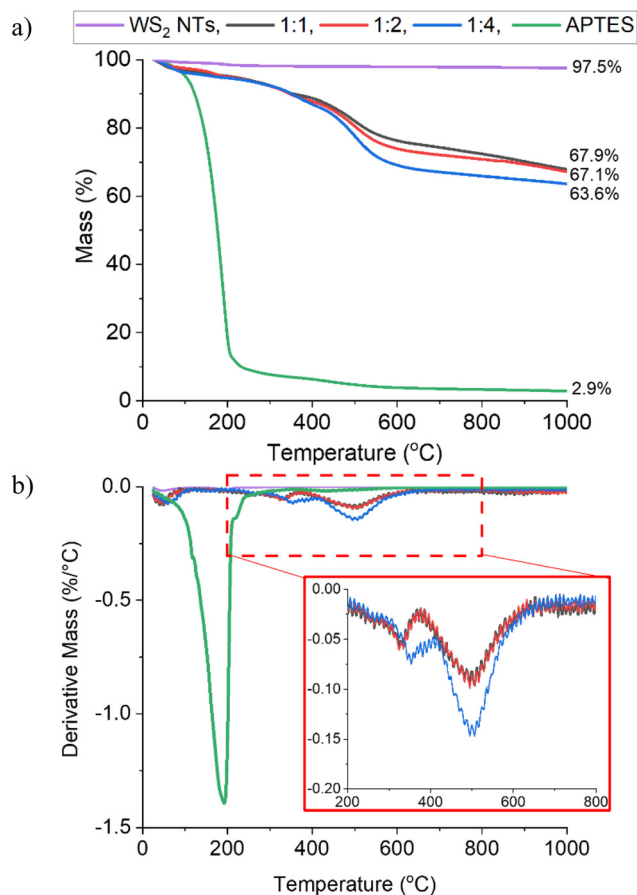


Fig. 2 (a) TGA weight loss curves and (b) DTA curves for WS₂ NTs, APTES and APTES modified WS₂ NTs at different ratios.

increased grafting of APTES at a ratio of 1 : 4 (WS₂ NT : APTES) and the formation of a siloxane network. The extent of the grafting was estimated from further analysis of the TGA data.⁵⁸ After mass normalization, the number of grafted chains were calculated using eqn (2):

$$\text{Chain}_{\text{graft}} = \frac{W_{\text{loss}}\%}{(100 - W_{\text{loss}}\%) \times M_{\text{w,molecule}}} \times N_{\text{a}} \quad (2)$$

where, $W_{\text{loss}}\%$ represents the percentage weight loss (from TGA) in the temperature range 200 °C and 800 °C, $M_{\text{w,molecule}}$ is the molecular weight of the grafted molecule of APTES (221.37 g mol⁻¹), and N_{a} is Avogadro's number (6.02214076 × 10²³). This temperature range was chosen assuming residual APTES was removed below 200 °C. Knowing the specific surface area (SSA_{BET}) of the WS₂ NTs,⁵⁹ from BET measurements = 19.19 m² g⁻¹ the coverage density (σ) can be readily calculated using eqn (3) and the values are listed in Table 1:

$$\sigma = \frac{\text{Chain}_{\text{graft}}}{\text{SSA}_{\text{BET}}} \quad (3)$$

The grafting density (σ) increases with increasing APTES concentration rendering the NTs more organophilic.

Table 1 Grafting density APTES on the surface of WS₂ NTs in air

| | $W_{\text{loss}}\%$ (200–800 °C) | $\text{Chain}_{\text{graft}}$ (mol g ⁻¹) | σ (mol nm ⁻²) |
|-----------------------------|-------------------------------------|---|-------------------------------------|
| WS ₂ APTES 1 : 1 | 22.55 | 7.92×10^{20} | 41.3 |
| WS ₂ APTES 1 : 2 | 28.41 | 1.08×10^{21} | 56.3 |
| WS ₂ APTES 1 : 4 | 35.14 | 1.47×10^{21} | 76.8 |

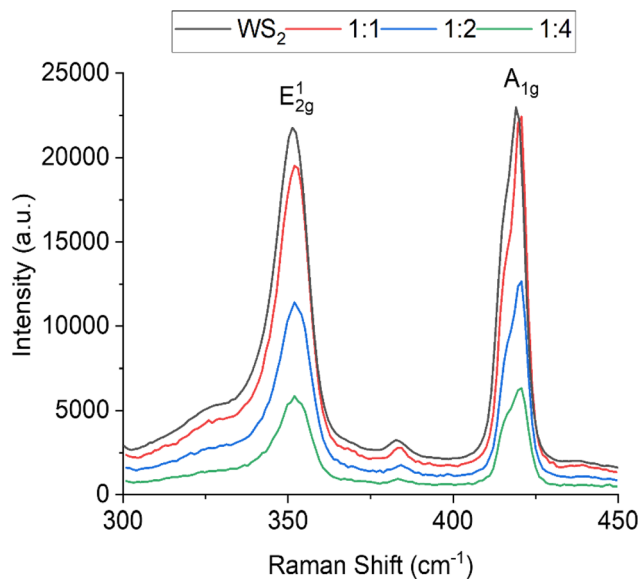


Fig. 3 Raman spectra of WS₂ NTs and APTES modified WS₂ NTs.

The Raman spectrum of WS₂ NTs displays peaks characteristic to WS₂ at 351.1 cm⁻¹ and 419.0 cm⁻¹, these are the most prominent Raman modes found in the spectra and are associated with the in-plane vibrations (E_{2g}) of chalcogen atoms and out-of-plane vibrations (A_{1g}) of chalcogen and transition metal atoms, respectively (Fig. 3).⁶⁰ After functionalization with APTES, a slight blueshift of both peaks, the E_{2g}^1 to 352.2 cm⁻¹ and the A_{1g} to 420.7 cm⁻¹ is observed for all APTES concentrations. This shift in peak position is representative of molecular absorption on the surface of the nanotubes.⁶¹ The A_{1g} peak can be seen to split and the FWHM (full width at half maximum) increases with increasing APTES concentration ($\Delta\text{FWHM} \approx 1.4$ cm⁻¹ from neat WS₂ NTs to WS₂ : APTES 1 : 4). Note that the splitting of the A_{1g} is attributed to the lower symmetry of the nanotube compared to the bulk, which induces a new peak B_{1u} at 416 cm⁻¹.⁶² The changes in the shape of the A_{1g} peak is evidence for covalent functionalization due to the presence of functional groups attached to the chalcogen atoms on the surface of the sulphur atom of the WS₂ NTs.⁶³ The covalent bonding of the APTES to the outermost sulfur leads to loss of symmetry enhancing the B_{1u} Raman peak, which is a silent mode in bulk WS₂. It should be noted that not only the addition of functional groups but also the structure (curvature) of the NTs can activate the B_{1u} mode. Additionally, with increasing APTES concentration, the intensity of the peaks

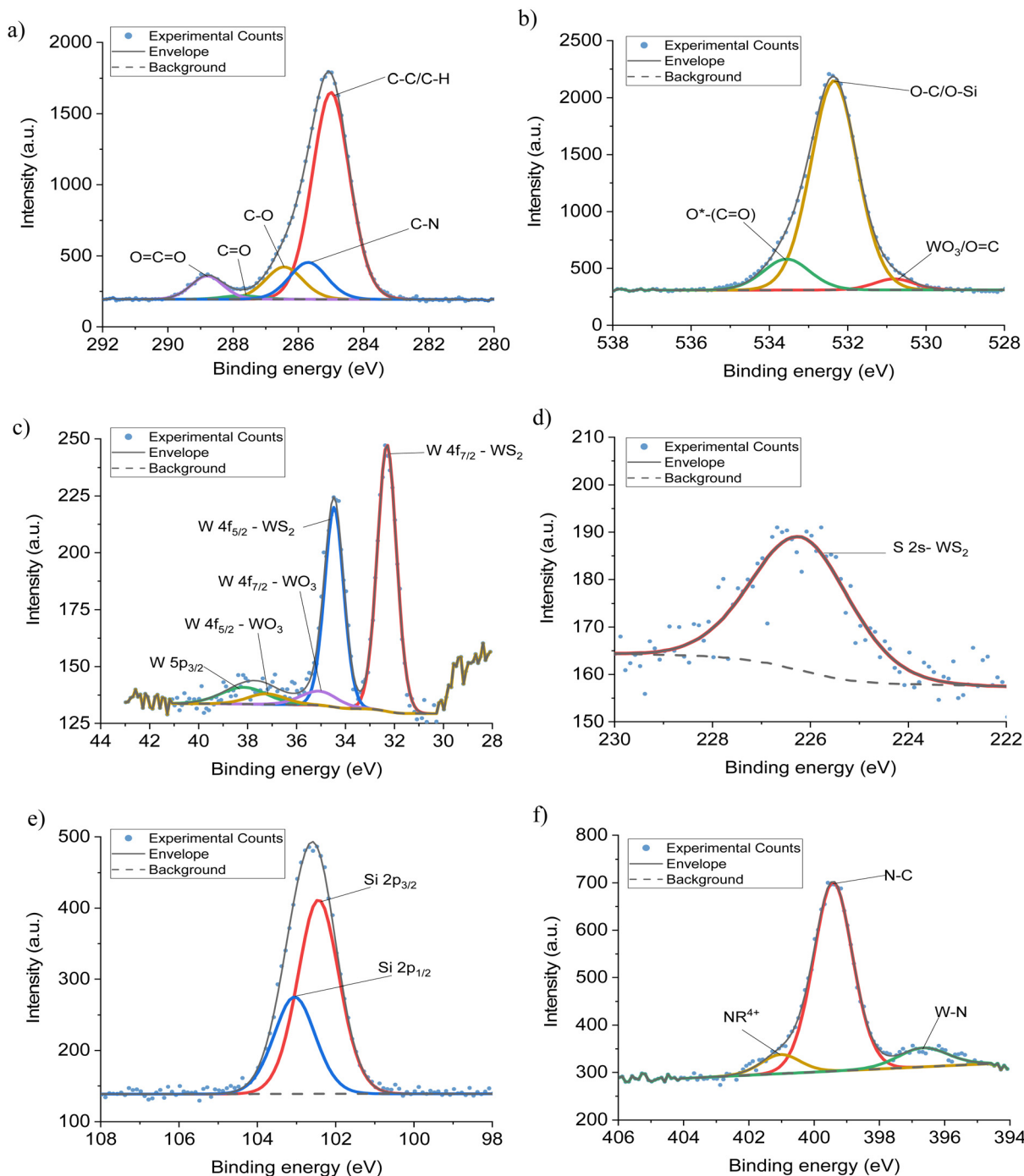


Table 2 Element atomic % extrapolated from deconvoluted XPS data for WS₂ NTs and APTES functionalized WS₂ NTs

| Sample | C | O | S | W | N | Si |
|-----------------------------|-------|-------|-------|-------|-------|-------|
| WS ₂ NTs | 19.97 | 7.25 | 49.26 | 23.51 | — | — |
| WS ₂ APTES 1 : 1 | 48.72 | 23.93 | 1.34 | 0.7 | 11.17 | 14.13 |
| WS ₂ APTES 1 : 2 | 60.98 | 22.83 | 1.21 | 0.64 | 5.61 | 8.73 |
| WS ₂ APTES 1 : 4 | 55.6 | 23.18 | 0.89 | 0.38 | 8.03 | 11.92 |

decreases, perhaps as a consequence of the APTES coating (siloxane network) on the surface of the NTs. These changes in the Raman spectra strongly support molecular physisorption of APTES on the surface of the WS₂ NTs.

To further determine if APTES functionalization of the WS₂ NT surface was successful, XPS spectra were recorded for all samples (deconvoluted curves are displayed in the ESI, see Fig. S1†) and the relevant atomic percentages are listed in Table 2. The atomic percentages are in agreement with our pre-

**Fig. 4** Deconvoluted XPS spectra, (a) C 1s, (b) O 1s, (c) W 4f, (d) S 2s, (e) Si 2p (f) N 1s regions from the XPS spectra of WS₂-APTES at a ratio of 1 : 4.

vious studies⁶⁴ confirming successful grafting of silane through carbon and oxygen. Both are loosely attached to the surface of the NTs due to atmospheric conditions, while Si and N are also detected for the WS₂ NTs : APTES samples. Increased atomic % for C and O (Table 2) in comparison to WS₂ NTs is ascribed to the successful attachment of APTES to the WS₂ NTs.

Fig. 4 shows representative deconvoluted spectra for the APTES functionalised WS₂ NTs. The remainder of the XPS data are presented in the ESI Fig. S2–S5 and Tables S2–S5.† Deconvoluted peaks in the C 1s region (Fig. 4(a)), display a similar chemical composition consisting of five components:

C–C/C–H, C–N, C–O, C=O, O=C–O. The addition of APTES on the surface of WS₂ NTs is identified with the evolution of a new peak at 285.7 eV from C–N bonding, characteristic of silane functionalisation of other NTs.²⁵ From the O 1s region (Fig. 4(b)) peaks derived from WO₃/O=C, O–C/O–Si and O* (C=O) were recorded. After functionalization with APTES, the evolution of another new peak at 532.35 eV was observed, corresponding to O–Si/O–C bonding. The O–C peak due to atmospheric contamination was present prior to the addition of the APTES. The increase in peak intensity relative to the other components suggests O–Si bonding, which overlaps with

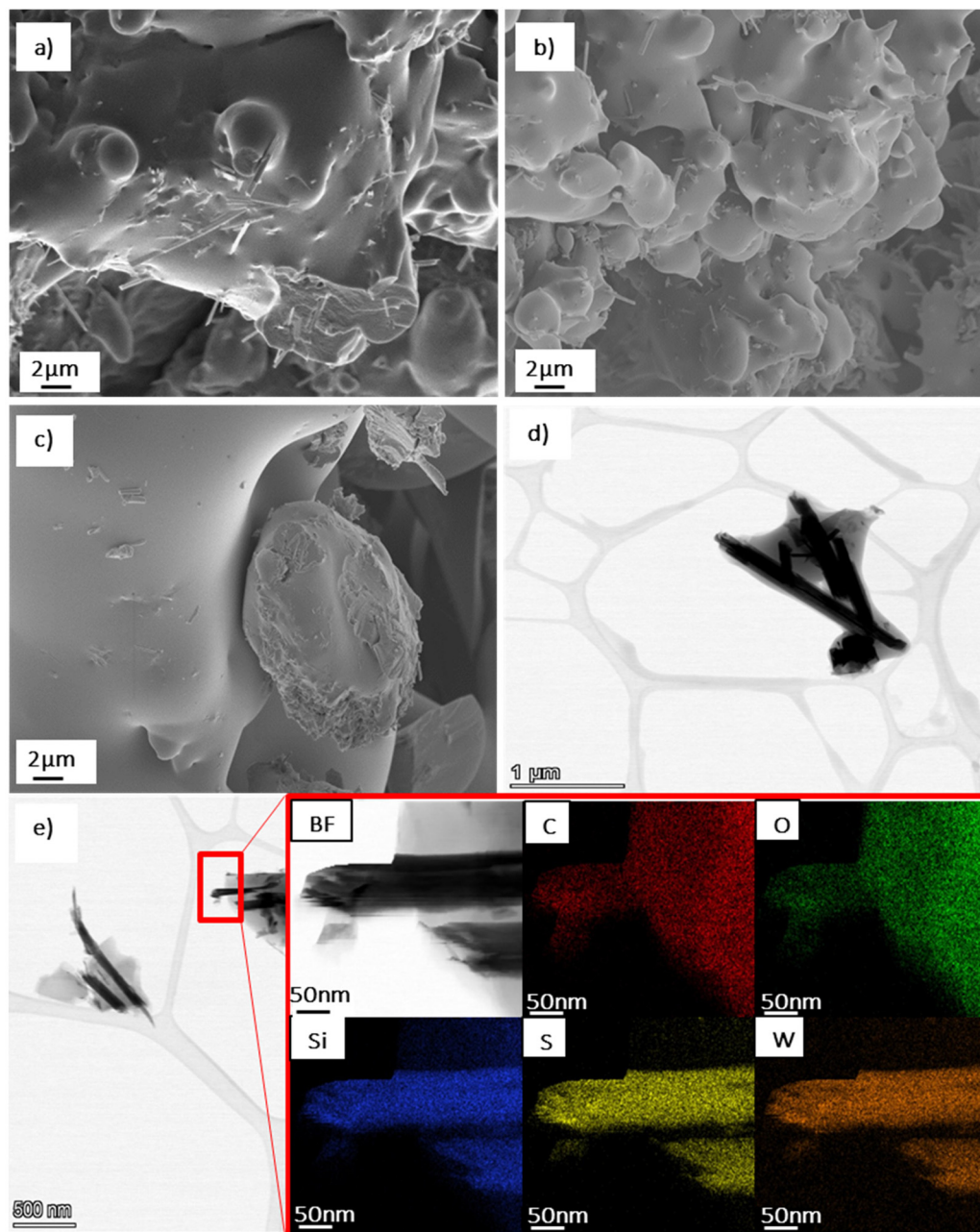


Fig. 5 SEM and STEM imaging of APTES functionalised WS₂ NTs. (a–c) SEM images of WS₂ NTs : APTES at 1 : 1, 1 : 2 and 1 : 4, respectively. (d) STEM of WS₂ NTs : APTES at 1 : 4, and (e) STEM and EDS mapping of the WS₂NTs–APTES 1 : 4 sample.



O–C in binding energy. An increase of approximately 12% in the area under the oxygen peak confirms binding of the APTES to oxygen, which is attached to the surface of the WS₂ NTs. The presence of different Si environments (Fig. 4(e)) is confirmed from deconvoluted Si 2p_{3/2} and Si 2p_{1/2} data which correlates with Si–O–C or Si–O–Si in the two energy states, again further affirming grafting of APTES to surface molecules on the WS₂ NTs. For the N 1s region (Fig. 4(f)) deconvoluted peaks corresponding to N–C, NR⁴⁺ and evidence of W–N bonding for the WS₂ NTs : APTES 1 : 4 sample were obtained. The N–C bonding is characteristic of APTES, showing it is successfully attached to the surface of the NTs.⁶⁵ NR⁴⁺ bonding is suggestive of an amine reaction between APTES with molecules on the surface of the WS₂ NTs, however this cannot be confirmed with these XPS spectra. Additionally, the observed W–N bonding confirms successful functionalization of APTES

to the WS₂ NTs, while it also suggests that by increasing the ratio of APTES to WS₂ NTs the grafting density of silane on the NT surface can be increased. For APTES functionalised WS₂ NTs, it should be noted that it is likely that the plasmon loss features from Si 2s photoemission overlap with the S 2p photoemission, possibly leading to incorrect identification of chemical environments and/or elemental composition. Therefore, for these samples, the S 2s region (Fig. 4(d)) was examined, however there is no indication of APTES interaction with sulphur atoms in this region.

SEM and STEM imaging were carried out to examine the NTs morphology after functionalisation with APTES, see Fig. 5. The WS₂ NTs were well dispersed in the APTES silane network, forming a cohesive continuous morphology at all ratios, see SEM images (Fig. 5(a)–(c)). This further supports strong interfacial interaction between the silane and the surface of the NTs. The aspect ratio of the NTs were also examined with NT lengths up to 6 μm measured, and a small portion of significantly shortened NTs (see STEM image in Fig. 5(d)), with lengths as small as 0.64 μm observed, most likely due to the sonication process during sample preparation.³ We reported the structure and morphology of the WS₂ NTs in great detail in our previous work.⁶⁴ From high resolution STEM images, (Fig. 5(d) and (e)), the APTES is seen to clearly coat the surface of the WS₂ NTs, an observation confirmed from EDS mapping. Tungsten (W) and sulphur (S) can be clearly identified for the NTs structure, while silicon (Si) from APTES is strongly attached to the surface of the NTs and is also surrounding the NTs. EDS analysis indicates also that carbon (C) and oxygen (O) (from the APTES) are found on the NT surface.

To confirm further the attachment of APTES to the surface of the WS₂ NTs, the zeta (ζ) potential of the WS₂ NTs and APTES modified NTs with increasing APTES concentration were measured in methanol dispersions. WS₂ NTs alone (1 : 0) have a charge of -26.7 ± 0.71 mV, due to the sulphur atoms exposed on the surface of the NTs.⁶⁶ After reaction with APTES, the ζ potential values gradually become increasingly

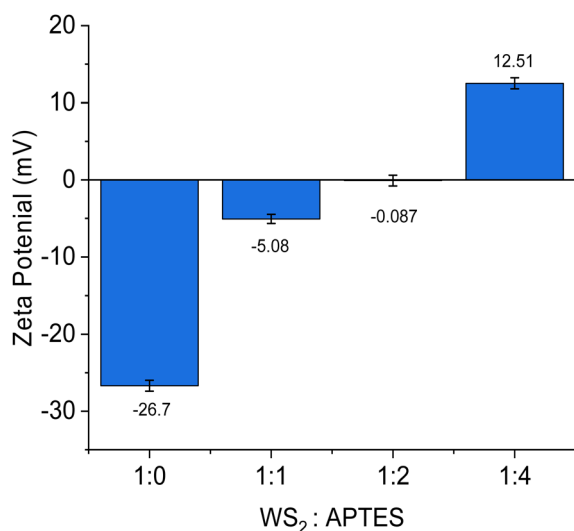


Fig. 6 ζ potential for WS₂ NTs, and change in ζ for APTES–WS₂ NTs with increasing APTES content.

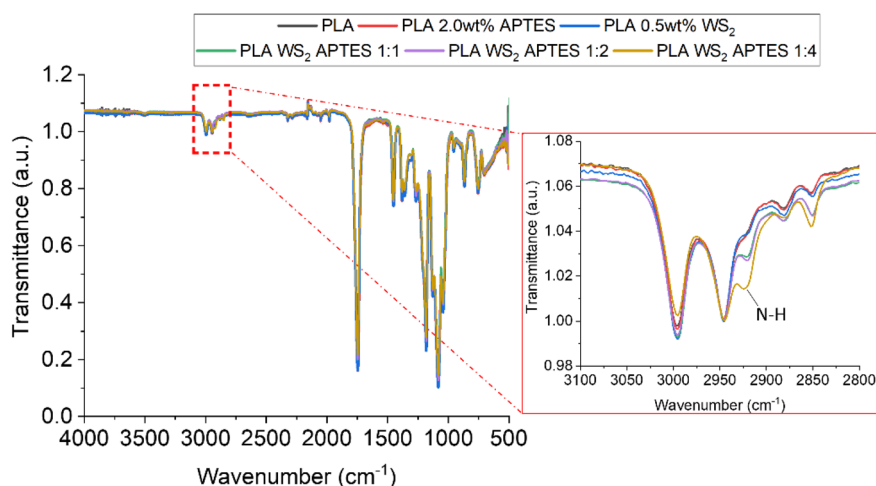


Fig. 7 FTIR spectra of PLA, a blend of PLA and APTES composites of PLA with APTES modified WS₂ NTs.



positive with increasing APTES concentration, Fig. 6. The concentration of APTES is critical to the extent of functionalization and APTES grafted to the surface of the WS₂ NTs. The change in ζ potential is derived from the presence of amine groups (from APTES) on the NT surface, as amine groups are protonated to positively charged ammonium producing a higher ζ potential value.^{65,67} This observation is a qualitative indication of successful functionalization of WS₂ NTs with APTES. The reaction between PLA and APTES follows a condensation and grafting mechanism that results in the formation of a N–H bond.⁶⁸ Consequently, there is the evolution of a band associated with N–H stretching at 2921 cm⁻¹ in the FTIR spectra that

becomes more intense and shifts by 4 cm⁻¹ to 2925 cm⁻¹ with increasing APTES content, see Fig. 7.

The rationale for functionalising WS₂ NTs with APTES is to provide a route to aid effective dispersion of the NTs in polymers and to promote strong interfacial interactions between both, such that some bulk properties of the polymer can be improved. To examine this hypothesis, APTES modified WS₂ NTs were dispersed in PLA and solvent cast to produce films and specimens for tensile mechanical testing.

The representative optical photographs shown in Fig. 8(a), compare film samples for neat PLA, composites of PLA and WS₂ NTs, and composites of PLA and APTES modified WS₂

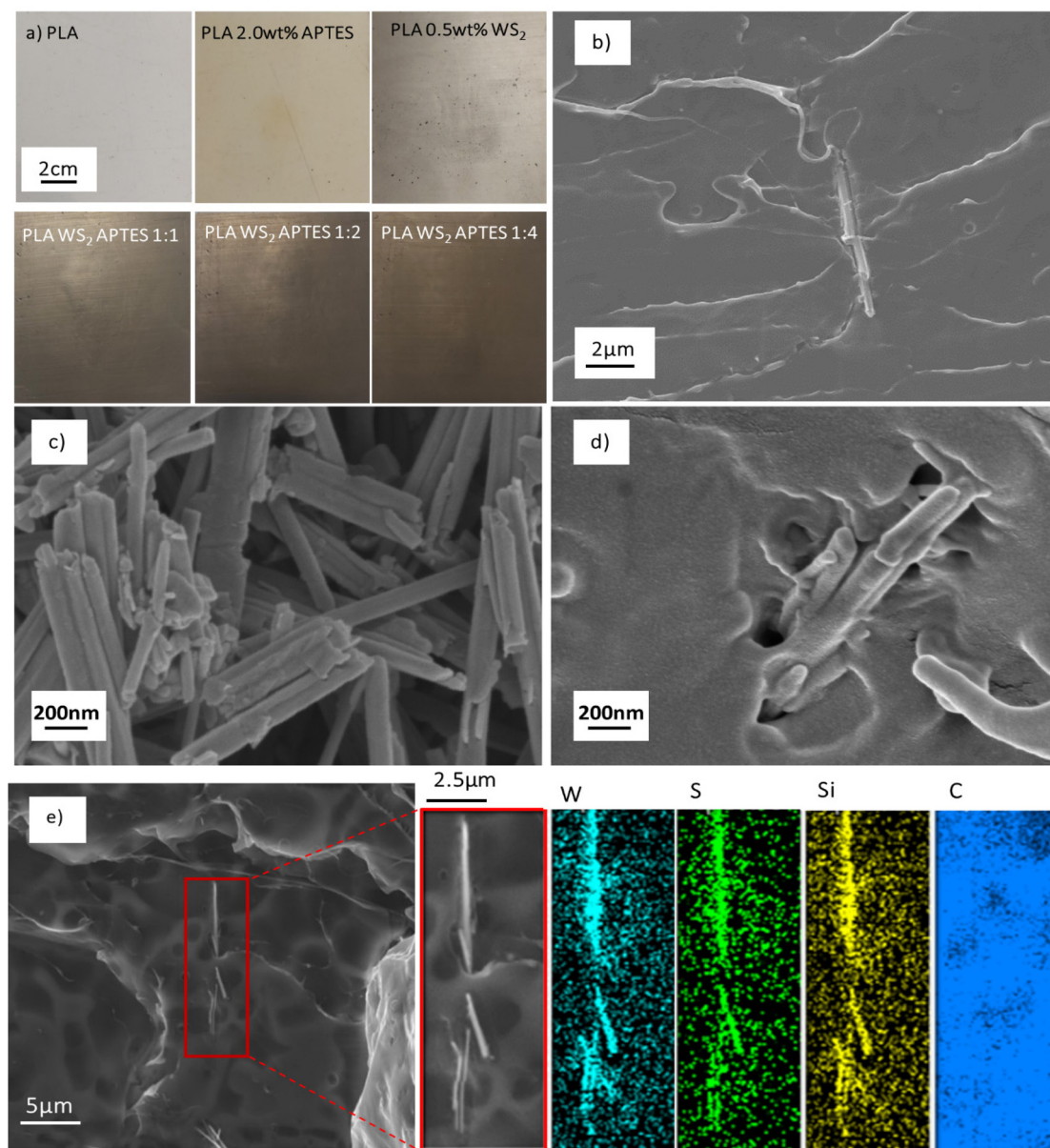


Fig. 8 (a) Representative optical photographs of film samples of PLA alone and corresponding composites and SEM micrographs of (b) composite of PLA and APTES modified WS₂ NTs (1 : 4), (c) unmodified WS₂ NTs, (d) composite of PLA and WS₂ NTs : APTES 1 : 4 at higher magnification and (e) composite of PLA WS₂ NTs : APTES 1 : 4 with corresponding EDS of highlighted area.



NTs. In agreement with previous studies, the WS₂ NTs disperse very well within the PLA matrix.^{43,48,69,70} Nevertheless, APTES functionalised WS₂ NTs are much more uniformly dispersed as clearly seen from these images suggesting increased surface interaction and compatibility between APTES modified WS₂ NTs and the PLA matrix. Extensive SEM imaging of the composites of PLA and APTES modified WS₂ NTs (Fig. 8(b) and (c)) across the length scales did not show NT agglomerations and individual NTs were observed (Fig. 8(b)), supporting uniform dispersion of the NTs in the PLA matrix. Additionally, SEM-EDS was used for surface elemental analysis of these composites, Fig. 8(e). This analysis clearly identifies tungsten and sulphur from the NTs, while also confirming the presence of silicon from APTES only on the surface of NTs, in agreement with the EDS analysis reported in Fig. 5. (The detected carbon on the entire analysed area stems from the carbon coating of the sample.) This observation is further verification of silane functionalisation of the WS₂ NTs.

To assess the effectiveness of silane modification of the WS₂ NTs on the mechanical properties of PLA, tensile tests of neat PLA, blends of PLA and APTES as control samples and, composites of PLA and APTES modified WS₂ NTs were measured. Representative stress–strain curves for all the specimens are shown in Fig. 9. The Young's modulus (MPa), maximum tensile stress (MPa), elongation at break (%) and the tensile toughness (kJ m⁻³) as a function of the ratio of WS₂ NTs:APTES were determined and the values are listed in Tables 3 and 4. For the blends of PLA and APTES only, *i.e.* with no WS₂ NTs added, neat PLA had an elongation at break of ~33% with stress oscillation observed beyond necking.⁷¹ Upon addition of 2 wt% APTES to PLA, an initial decrease in tensile properties is observed before an increase to values approaching that of the PLA alone (Table 3). The mechanical properties with 1.0 wt% APTES loading exhibit reduced performance compared to neat PLA, which may be associated with aminolysis causing scission of the polymer chains and the material becomes brittle.^{68,72} However, at 2 wt% APTES the mechanical properties are similar to that of neat PLA. This suggests that at 2.0 wt% APTES there is strong interfacial interactions with the polymer chains and the microstructure of PLA is not degraded when mixed with APTES. The inclusion of 0.5 wt% unfunctionalised WS₂ NTs resulted in a degradation of mechanical properties, ~15% reduction in Young's modulus relative to neat PLA, indicative of poor interfacial interaction between the WS₂ NTs and the PLA matrix,⁷³ resulting in a reduction in PLA ductility and toughness. In contrast, inclusion of APTES functionalised WS₂ NTs to the same PLA resulted in a systematic increase in the tensile mechanical properties with increasing WS₂ NTs:APTES ratio, Fig. 9(b). When the ratio of WS₂ NTs:APTES was 1:4 there was an enhancement in mechanical properties, including an almost 600% increase in elongation at break and tensile toughness from 0.99 kJ m⁻³ to 6.88 kJ m⁻³ (Table 4). Critically, there was little change in the maximum tensile strength and Young's modulus of PLA, irrespective of the WS₂ NT:APTES ratio. The significant increase in elongation at break and toughness on addition of APTES modified

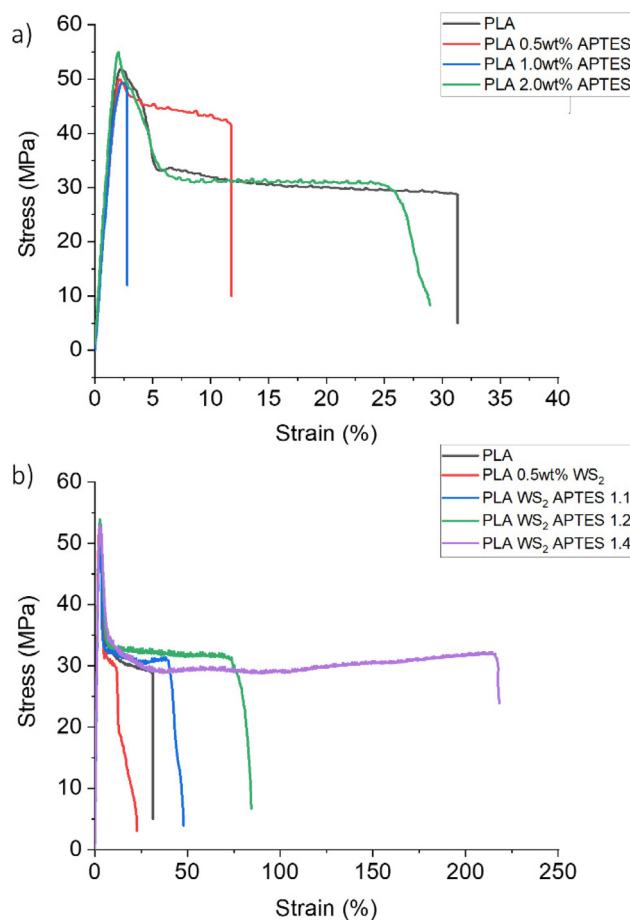


Fig. 9 Representative stress–strain curves for neat PLA relative to those for (a) blends of PLA and APTES and (b) composites of PLA and APTES modified WS₂ NTs.

Table 3 Tensile mechanical properties of PLA and blends of PLA and APTES

| Sample | Modulus (MPa) | Maximum tensile stress (MPa) | Elongation at break (%) | Tensile toughness (kJ m ⁻³) |
|-------------------|---------------|------------------------------|-------------------------|---|
| PLA | 3414 ± 178 | 57 ± 4 | 33 ± 4 | 1.0 ± 0.10 |
| PLA 0.5 wt% APTES | 3085 ± 114 | 50 ± 4 | 17 ± 3 | 0.4 ± 0.05 |
| PLA 1.0 wt% APTES | 2883 ± 73 | 49 ± 2.5 | 3.3 ± 0.3 | 0.1 ± 0.02 |
| PLA 2.0 wt% APTES | 3439 ± 72 | 54 ± 3 | 31 ± 2.5 | 0.9 ± 0.03 |

Table 4 Tensile mechanical properties of PLA and composites of PLA APTES modified WS₂ NTs

| Sample | Modulus (MPa) | Maximum tensile stress (MPa) | Elongation at break (%) | Tensile toughness (kJ m ⁻³) |
|-------------------------------|---------------|------------------------------|-------------------------|---|
| PLA | 3414 ± 178 | 57 ± 4 | 33 ± 4 | 1.0 ± 0.10 |
| PLA 0.5 wt% WS ₂ | 2922 ± 148 | 54 ± 4 | 23 ± 2 | 0.6 ± 0.08 |
| PLA WS ₂ APTES 1:1 | 3222 ± 179 | 52 ± 3 | 51 ± 6 | 1.5 ± 0.25 |
| PLA WS ₂ APTES 1:2 | 3493 ± 102 | 53 ± 1 | 84 ± 14 | 2.6 ± 0.40 |
| PLA WS ₂ APTES 1:4 | 3323 ± 151 | 55 ± 2 | 208 ± 18 | 6.9 ± 0.41 |



WS₂ NTs is a consequence of the improved and very strong interfacial interactions between the NTs and polymer and the role APTES is playing in aiding the dispersion of WS₂ NTs in the PLA matrix. The interaction *via* the amine and hydroxyl groups of APTES bound to the NTs and PLA provides a route for effective stress transfer at the interface from the polymer to the filler.

Given the fact that many nanomaterials can nucleate polymers and alter the crystallization behaviour of the matrix, the thermal properties of the composites were studied by DSC. DSC curves (cooling and melting curves) for unfilled PLA, blends of PLA and APTES, composites of PLA and unmodified WS₂ NTs and composites of PLA and APTES modified WS₂ NTs were recorded, see Fig. 10.

The T_g of neat PLA was determined to be 54 °C and it remained constant on the addition of APTES or WS₂ NTs (Table 5). However, on addition of APTES modified WS₂ NTs,

Table 5 DSC parameters for neat PLA, blends of PLA and APTES, and composites of PLA and APTES modified WS₂ NTs

| Sample | T_g (°C) | T_{cc} (°C) | ΔH_{cc} | T_{m1} (°C) | T_{m2} (°C) | ΔH_m | X_c (%) |
|---------------------------------|------------|---------------|-----------------|---------------|---------------|--------------|-----------|
| PLA | 54 | 113 | 25 | 151 | 156 | 27 | 1.7 |
| PLA/0.5 wt% APTES | 54 | 113 | 25 | 151 | 156 | 27 | 2.7 |
| PLA/1.0 wt% APTES | 53 | 109 | 28 | 150 | 156 | 29 | 0.9 |
| PLA/2.0 wt% APTES | 54 | 112 | 27 | 153 | 155 | 29 | 2.1 |
| PLA/0.5 wt% WS ₂ | 54 | 118 | 24 | 153 | — | 28 | 4.2 |
| PLA WS ₂ APTES 1 : 1 | 56 | 122 | 24 | 154 | — | 28 | 3.6 |
| PLA WS ₂ APTES 1 : 2 | 56 | 121 | 25 | 153 | — | 27 | 2.5 |
| PLA WS ₂ APTES 1 : 4 | 56 | 121 | 23 | 153 | — | 25 | 2.5 |

the T_g of PLA increased by 2 °C, although this is likely to be within instrument error. Given the fact that the change in T_g was minor, as was the case with the Young's modulus and tensile strength of PLA on inclusion of silane functionalised WS₂ NTs, the change in the mechanical properties are not due to a plasticizing effect or major change in the PLA crystalline content.⁷⁴

Moreover, the PLA used in this study was highly amorphous (at least 96% L-isomer) and the minor crystalline component very slow to crystallise, such that no crystalline peak is observed in the cooling curve (Fig. 10(a)). However, a significant broad cold crystallisation peak is observed in the heating cycle (Fig. 10(b)) for all the samples. The neat PLA has a broad T_{cc} peak centred at 113 °C, while the incorporation of WS₂ NTs shifted the T_{cc} by 5 °C to 118 °C. The NTs have a strong nucleating effect on the PLA, but a limited effect on the overall crystalline content ($X_c = 4.2\%$) due to the high L-isomer content. There is a further shift of 3 °C in T_{cc} to 121 °C upon inclusion of the APTES modified WS₂ NTs. This further shift, some 8 °C higher than that for unfilled PLA is a consequence of the better WS₂ NT dispersion and increased NT surface area available as nucleating sites for the polymer, but again the high L-isomer content hinders crystallite growth. A doublet of melting peaks were observed for the neat PLA and blends of PLA and APTES with T_{m1} at 151 ± 1 °C and T_{m2} at 155–156 °C. Both peaks are characteristic of PLA and can be attributed to the melting–recrystallization–melting processes of PLA lamellae. The first peak is ascribed to the melting of new lamellae formed during the heating cycle (*i.e.* T_{cc}), the second peak is the melting–recrystallisation of primary thin lamellae at relatively higher temperature.⁷⁵ Interestingly, the DSC curves for the composites of APTES modified WS₂ NTs and PLA exhibit a single melting peak at 152 °C, which is attributed to the highly dispersed modified NTs promoting nucleation and PLA crystal growth. However, due to slow crystallisation kinetics of the PLA used in this study, the composites remain almost fully amorphous with a crystalline content remaining below 5%. Therefore, the significant enhancement in the ductility and toughness of the PLA on inclusion of APTES modified WS₂ NTs must be derived from the high level of dispersion and strong interfacial interactions between the APTES coated NTs and the polymer matrix and not because of changes in the PLA microstructure.

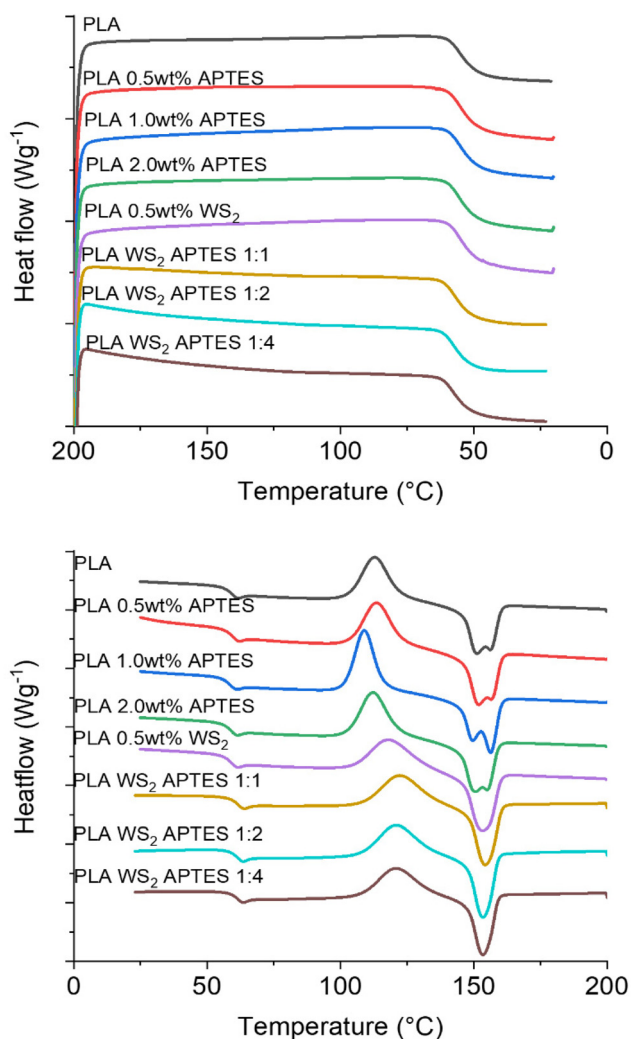


Fig. 10 DSC thermograms for PLA and its blends with APTES and composites with APTES modified WS₂ NTs showing (a) first cooling cycle and (b) second heating cycle.



4. Conclusions

(3-Aminopropyl) triethoxysilane (APTES) was successfully grafted to the surface of WS₂ NTs, the greater the concentration of APTES used the greater the extent of its binding to the NT surface. Extensive characterisation of the APTES functionalised WS₂ NTs using a combination of spectroscopy (FTIR, Raman, XPS), thermal-gravimetric analysis (TGA), electron microscopy (SEM-EDS, STEM-EDS) and Zeta potential measurements confirmed a high level of grafting of the APTES through the formation of siloxane networks on the NT surface. Additionally, the APTES was covalently bonded owing to the presence of functional groups attached to the surface sulfur atoms of the WS₂ NTs. APTES modification of the WS₂ NT surface significantly improved the extent of WS₂ NT dispersion in the PLA matrix and promoted strong interfacial interactions between the NTs and the polymer. This resulted in a significant increase in the elongation at break, by 600%, and the tensile toughness of PLA from 1.0 kJ m⁻³ to 6.8 kJ m⁻³ (~600%) on inclusion of WS₂ NTs:APTES (1:4). This work highlights for the first time the effectiveness of silane functionalization of 1D WS₂ nanotubes as a route to forming strong interfacial interactions between inorganic nanoparticles and polymers to produce composites with significantly enhanced ductility and toughness without sacrificing stiffness and strength, properties useful for food packaging or biomedical applications. Specifically, given the excellent combination of increased tensile strength and toughness obtained in this work, combined with the known radio-opacity and non-toxicity of WS₂ NTs and, the biocompatibility of PLA, reinforcement of PLA with WS NTs may find application as Bioresorbable Vascular Scaffolds (BVS).

Conflicts of interest

There are no conflicts to declare.

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