TEKSTİL VE KONFEKSİYON

Vol: 34, No: 1
DOI: 10.32710/tekstilvekonfeksiyon. 1117280

Effects of Different Types of Surfactant Treatments on the Electromechanical Properties of Multiwalled Carbon Nanotubes Decorated Electrospun Nanofibers

Abdulkadir Şanlı [1] 0000-0002-9768-9005
Şule Pınar Cinfer[2] 0000-0003-1075-0609
Afife Binnaz Hazar Yoruç[3] 0000-0001-7281-2305

[1] Faculty of Engineering, Department of Mechatronics Engineering, Turkish-German University, 34820, Beykoz, Istanbul, Turkiye
[2] Yıldız Technical University / Faculty of Chemical and Metallurgical Engineering, Department of Metallurgical and Materials Engineering / Davutpaşa Mah. Davutpaşa Caddesi, 34210 Esenler, Istanbul, Turkiye
[3] Yıldız Technical University / Faculty of Chemical and Metallurgical Engineering, Department of Metallurgical and Materials Engineering / Davutpaşa Mah. Davutpaşa Caddesi, 34210 Esenler, Istanbul, Turkiye

Corresponding Author: Abdulkadir Şanlı, a.sanli@imperial.ac.uk

ABSTRACT

Carbon nanotubes (CNTs) have a strong tendency to form agglomeration due to van der Waals interactions, which hinders their practical utilization. Therefore, an effective and stable dispersion of CNTs in a surfactant based solvent is very important for the realization of CNTs based nanocomposites in various applications. In this paper, influence of different types of surfactant on the electromechanical properties of multiwalled carbon nanotubes (MWCNTs) decorated electrospun thermoplastic polyurethane (TPU) nanofibers were investigated by UV-VIS spectroscopy, zeta potential, FT-IR analysis, scanning electron microscopy (SEM) and uniaxial tensile strain sensing. Obtained results suggest that type of surfactant has not only effecting the dispersion level of CNTs but also has a significant influence on the electromechanical properties of CNTs decorated elecrospun CNTs/TPU nanofibers. The results of the present study provide new insights into the design and tailoring the electromechanical properties of CNTs decorated electrospun nanofibers.

ARTICLE HISTORY
Received: 16.05.2022
Accepted: 08.11.2022

KEYWORDS

Multiwalled carbon nanotubes, thermoplastic polyurethane, electrospinning, nanofibers

1. INTRODUCTION

Among various carbonaceous nanofillers, carbon nanotubes (CNTs) has inspired many scientist owing to their unique physical properties which make them ideal as reinforcing material for high performance nanocomposites. High performance nanocomposites can be synthesized by combining them with CNTs that enables their usage in numerous industrial applications including flexible electronics [1], mechanical sensors [2-7] electromagnetic interference shielding [8] etc. Fabrication of high performance CNTs based nanocomposites still challenging since CNTs have a great tendency of forming bundles due to strong van der Waals interactions [9, 10]. These bundles and agglomerations cause a deterioration in the mechanical and electrical properties of CNTs based composites [11, 12]. Realization of aforementioned applications of CNTs based nanocomposites can be achieved by ensuring a reliable and effective dispersion of CNTs. To break down the CNTs bundles or agglomerates and disperse them in surfactant containing solution, several approaches including mechanical methods and physical (non-covalent) or chemical (covalent) processes have been adopted to their surface energies [13, 14]. It has been reported that surface modification of CNTs by introducing functional groups, which interacts with surfactant through polar- polar interaction resulting prevention of CNTs to form bundles that helps to better and more stable dispersion [15]. Chemical methods are surface functionalization methods used to improve properties such as wettability, agglomeration, chemical compatibility. With the functionalization process, the dispersibility, reactivity, processability and biocompatibility of CNTs can be increased [16]. Non-covalent surface treatments are a preferred method because of the ability to adsorb various functional groups to the surface without disturbing the structures of π-bonds in

To cite this article: Şanlı A, Cinfer Ş P, Hazar Yoruç A B. 2024. Effects of different types of surfactant treatments on the electromechanical properties of multiwalled carbon nanotubes decorated electrospun nanofibers. *Tekstil ve Konfeksiyon*, 34(1), 11-.18

graphene sheets [17]. However, surfactants and polymers that can be used in this functionalization process are limited and their dispersions are not stable. Functionalized CNTs are difficult to re-modify. Covalent functionalization can greatly improve the solubility, dispersibility and chemical compatibility of CNTs. Covalent functionalization occurs when the π-bonds in the basic structures of CNTs are broken, and the functional group is bonded by forming a covalent bond that shares at least one electron with the functional group. It is this deterioration and restructuring in the structure that changes and improves the properties of the CNTs [18-20]. Mechanical methods such as ultrasonication and high shear mixing on the other hand can indeed separate the CNTs from each other. However, with increasing time and power aspect ratio of CNTs can shorten the by breaking the tubes.

For the modification of CNTs in the preparation of CNTs based polymer nanocomposites various surfactants are employed [21-24]. Depending on the polarity of the surfactant head group, surfactants can be categorized into four types, which are non-ionic, anionic, cationic, and amphoteric [25]. Among various surfactants, sodium dodecyl sulfate (SDS) and cetyltrimethylammonium bromide (CTAB) have drawn attention. SDS is an organic compound and it is the most widely studied anionic (negatively charged) surface agent. It consists of a head and tail with amphiphilic properties, consisting of a 12-carbon chain attached to a sulfate group [26]. At low concentrations of SDS, which allows the CNTs to be suspended, CNTs agglomeration can be observed even after ultrasonication. By increasing and optimizing the SDS concentration, a homogeneous carbon nanotube solution appearance can be achieved [27, 28]. CTAB on the other hand is an important cationic (positively charged) surfactant consisting of a head with three methyl and an ammonium group and a tail with 16 carbons [29]. It is used as coating, stabilization and passivation agent. Through CTAB modification sensitivity and detection limits of materials can be improved by increasing their detection performance. To date, there are various studies dealing with the role of the surfactants on the dispersion of CNTs and their mechanisms [30-35]. Zou et al. [35] conducted the absorbance of CNTs: polycarboxylate-based cement superplasticizer at different concentrations at different sonication energies. It was seen that absorbance rate increases gradually with the increase of the sonication power that is proportional to the CNTs concentration. Recently, Rajendran et al. [33] has studied a comparative analysis of the dispersion of CNTs in polar solvents. It was suggested that the degree of affinity CNTs with -COOH group depends on the polarity of the solvent type. Chatterjee et al. [36] investigated the effect of the different surfactants i.e. DOC, SDBS, CTAB, BnzlkCl, and TX405 on the selectivity and sensitivity of CNTs based volatile organic compounds (VOC) biomarkers of lung cancer. For the assessment of the influence of surfactant type on the properties of MWCNTs decorated electrospun nanofibers, there are still various aspects to be investigated. In this work, the effect of dispersion type on the properties of -COOH functionalized MWCNTs-TPU based nanofibrous structures fabricated by electrospinning technology was investigated. Samples were fabricated by dip coating electrospun TPU nanofibers into MWCNTs based dispersed solution. Dispersion quality of MWCNTs were assessed by UV-Vis and Zeta potential analysis. Results are finally further discussed by assessing FTIR, SEM, 2P-4P probe electrical resistance and uniaxial tensile strain measurements.

2. MATERIAL AND METHOD

2.1 Materials and Chemicals

From Molchem Technologies (London, United Kingdom) purchased industrial –COOH functionalized MWCNTs has 92% purity and 8– 15 nm outer diameter. Thermoplastic polyurethane (TPU) (Elastollan 1185A10) was obtained from Biesterfeld in granule form with 1.12 kg/dm^3 density, N, N-Dimethylformamide (DMF), Sodium Dodecyl Sulfate (SDS) and Cetyltrimethylammonium bromide (CTAB) were bought from Labor Teknik (Istanbul, Turkey), Akbel Kimya (Bursa, Turkey) and Alfa Aesar (Thermo Fisher GmbH, Germany), respectively. All chemicals used in this study were used and received without any further treatment.

2.2 Characterization of electrospun MWCNTs/TPU Nanofibers

To understand the morphology as well as complex piezoresistive behavior of MWCNTs/TPU nanofibers, various characterization methods including SEM, U-Vis, FTIR, Zeta potential, 2-point and 4-point probe resistance measurements and uniaxial loading measurements were conducted. For the electrospinning process, samples were electrospun by an electrospinning unit (Inovenso NS24XP). SEM analysis (Zeiss Supra 55 VP) was used to see the microstructure and dispersion quality of the fibers decorated with MWCNTs. To do this, all samples were coated with gold and all analysis was performed at 10 kV and 13 mm WD (work distance). In order to determine the stability of the mixed solutions containing MWCNTs/surfactant agents, samples were analyzed by UV-Vis Spectroscopy (NanoPlus). For the precipitation of the MWCNTs contained solutions for UV-Vis analysis, the solutions were first centrifuged by a centrifugation device (Hermle Z206A) at 6000 rpm for 30 minutes and then passed through a 0.2 µm Polytetrafluoroethylene (PTFE) filter syringe. FTIR analysis was performed with Bruker brand Tensor 27 model device in order to see interface interaction between TPU fibers and dispersed MWCNTs structures. To perform electrical measurements (2-point probe resistance measurement), copper tapes were applied on the both side of films with a distance of 3 cm. A digital multimeter (Fluke 179) with a resolution of 0.1 Ω was then used to measure the electrical resistance of the electrospun TPU films coated with MWCNTs. Moreover, a high precision instrument (Keithley 2400) was used to evaluate surface resistivity measurements (4-point probe resistance measurement). The average of the measurements taken from 10 different locations in the area between the copper wires was calculated. Subsequently, to see the relative

resistance change of the electrospun MWCNTs decorated TPU samples under uniaxial strain, a custom-made uniaxial strain device was used. Here, samples were fixed from one side and pulled from the other side with a strain rate of 1 mm/hour through a system controlled by a microprocessor (Arduino Nano) and a stepper motor (17HS4401 Nema 17 Step Motor). During the uniaxial strain measurements, corresponding resistance values was measured by a Fluke 179 multimeter.

2.3 Synthesis of electrospun MWCNTs/TPU Nanofibers

For the synthesis of MWCNTs decorated electrospun TPU nanofibers shown in Figure 1, TPU granules were first dried in a vacuum oven at 100 °C for 3 h to remove any absorbed moisture on them. After that, 1.5 g of TPU granules were dissolved in 10 ml of DMF solvent. Here, TPU solution was prepared without any additives by mixing it with DMF mixture by magnetic stirrer for 2 h at 60 °C to ensure complete dissolution and a homogeneous solution for electrospinning. After that, as a first part of synthesis of MWCNTs decorated electrospun TPU fibrous film, TPU:DMF mixture was taken to a 10 ml syringe and placed in the syringe pump. Subsequently, dissolved TPU solution was electrospun by electrospinning unit (Inovenso NS24XP) with following parameters: applied voltage (15 kV), collector speed (700 rpm), feed rate (3 ml/h), tip to collector distance (20 cm) and spinning time (2 h). Here, the tip of the syringe was set to move 40 mm from left to right at the speed of 20 mm/h. The ambient temperature and humidity were set 25 ± 2°C and 60 ± 5 RH%, respectively. Electrospun thin layer of TPU was then removed carefully from the thin aluminum layer wrapped around the rotating collector with an average diameter of 10 cm to 10 cm. Then in total 3 samples were cut in the dimensions of 3 cm x 6 cm for further characterizations. As a next step shown in Figure 2, MWCNTs were dispersed in two different surfactants, which are SDS and CTAB. To do this, MWCNTs/surfactant solutions for a pre-determined concentration of 1 wt.%/v were prepared. Prepared solutions were sonicated in ultrasonic bath for 1 h. Finally, electrospun samples were immersed in MWCNTs based dispersions and this mixture further sonicated in ultrasonic bath for 60 min to ensure the electrical conductivity. Then, samples were washed several times by distilled water and finally dried in oven at 60 °C for 1h. The appearance of the electrospun TPU sample is white color while it turned to the black after dipping into the MWCNTs dispersion.

3 RESULTS AND DISCUSSION

Obtained results with respect to microscopic tests, UV-Vis, FTIR, Zeta potential as well as electrical properties of MWCNTs decorated electrospun MWCNTs/ TPU for different MWCNTs dispersions are given in detailed below. From the SEM images taken for electrospun TPU nanofibers (Figure 3), it is seen that electrospun TPU fibers exhibit relatively smooth and homogenous distribution. From the fiber thickness distribution measurements taken by ImageJ software [37] (Figure 4), the mean value of TPU fibers thickness are around 1.28 ± 0.788 µm. Further, the morphology of dispersed MWCNTs decorated electrospun TPU nanofibers shown in Figure 5. Compared to the MWCNTs: CTAB/TPU samples MWCNTs are dispersed more homogeneously and therefore attached more on the TPU fibers for MWCNTs: SDS/TPU samples. Hence, it was expected that this will led to better electrical properties due to the contribution of more MWCNTs to the network.

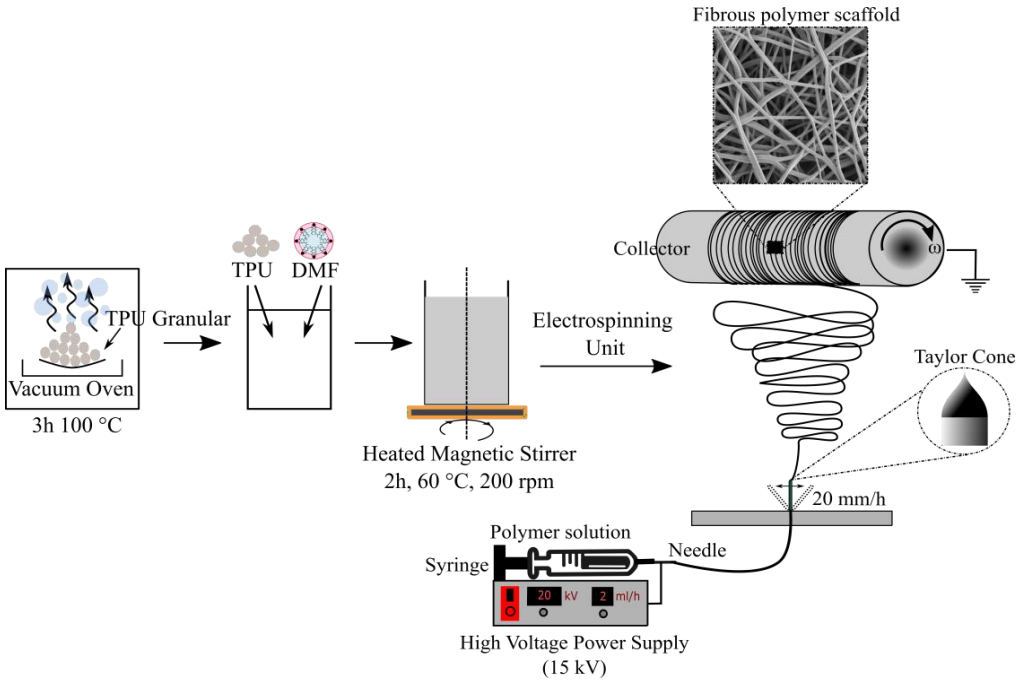

Figure 1. A detailed schematic illustration of the fabrication process of electrospun TPU and corresponding electrospinning unit

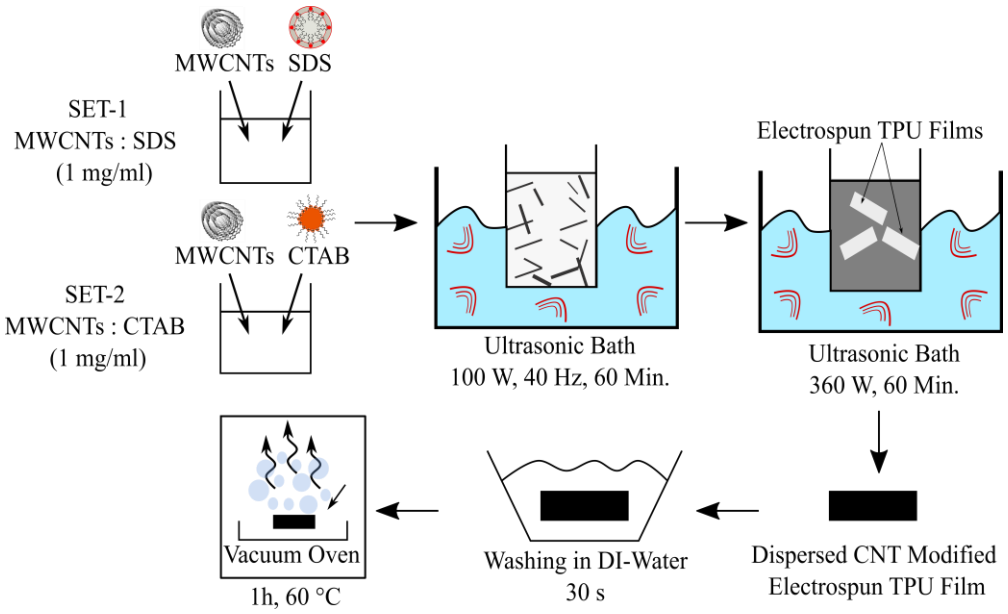

Figure 2. Schematic representation of dispersion of MWCNTs at different surfactants and decoration of electrospun TPU nanofibers by dipping them in dispersed MWCNTs-surfactant solutions

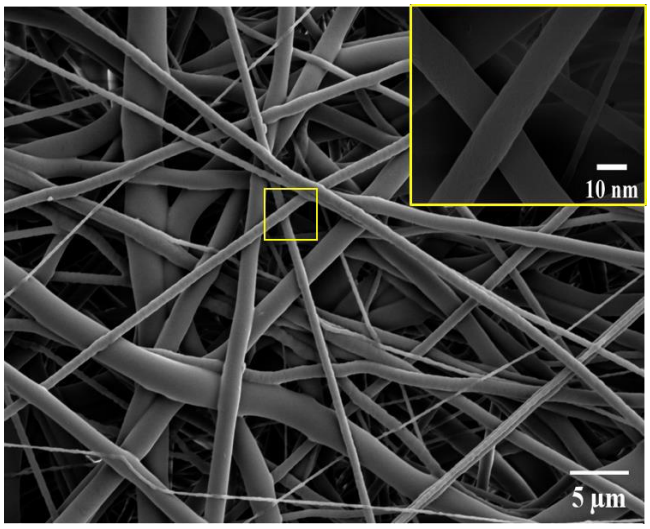

Figure 3. Morphology and structure of electrospun TPU fibers. Inset shows closer image of morphology of TPU fibers

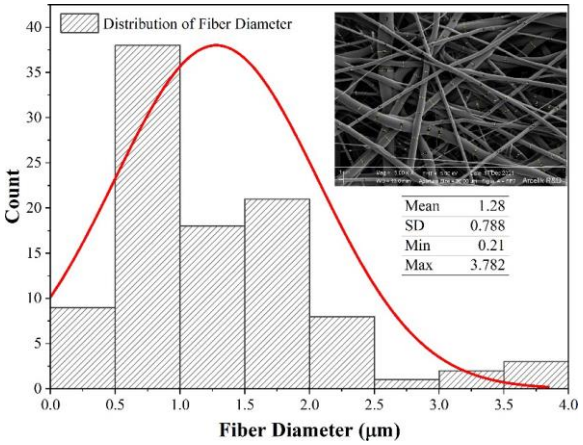

Figure 4. Distribution of fiber diameter of electrospun TPU fibers calculated by ImageJ software

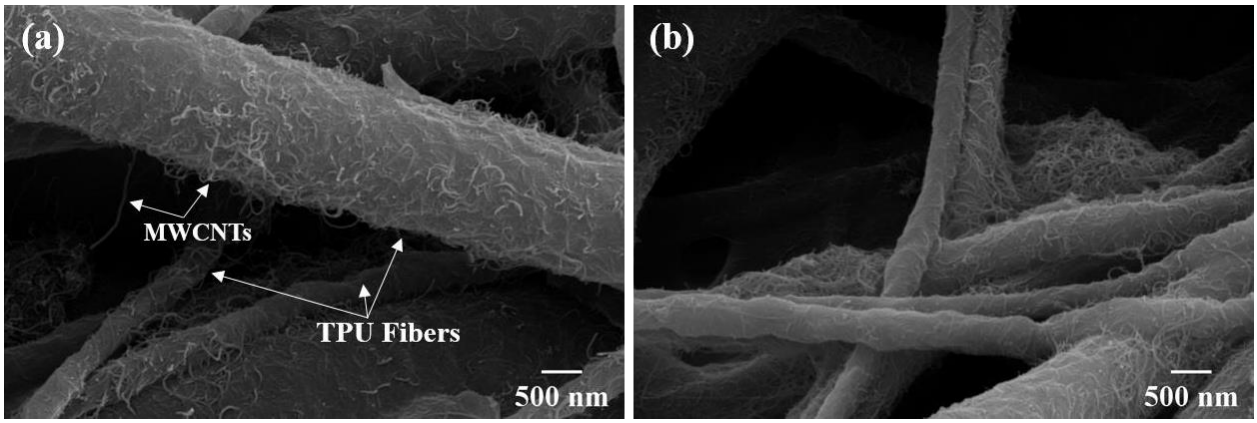

Figure 5. SEM image of electrospun (a) MWCNTs-SDS/TPU and (b) MWCNTs-CTAB/TPU sample. Here, MWCNTs concentration is set for both sample as 1 wt.%/v

UV-Vis analysis was performed to determine the dispersion efficiency of MWCNTs in MWCNTs-surfactant solutions. Owing to 1D van Hove singularities, individual CNTs exhibit characteristic bands and they are active in the UV-vis region. Whereas, agglomerated carbon nanotubes do not exhibit active behavior at wavelengths between 200-1200 nm [38-40]. Therefore, it is possible to relate the amount of individual CNTs dispersed in solution to the absorption intensity [41]. Figure 6 shows the UV-Vis spectra of bundled MWCNTs, MWCNTs-SDS and MWCNTs-CTAB solutions. It is clear to see that non-sonicated MWCNTs show almost no absorption in the UV-spectrum (see inset Figure 6a) due to existence of big agglomerates due to strong van der Walls attractions between the CNTs [42]. Introduction of SDS and CTAB surfactants with provided mechanical energy with sonication overcame the strong van der Walls interactions that lead to disentanglement of MWCNTs. Through UV-Vis spectra, it is seen that absorbance for both MWCNTs-SDS and MWCNTs-CTAB solutions give maximum peak between 200 nm and 250 nm and this absorbance gradually decreases [43]. It is important to note that, compared to the CTAB, dispersions with SDS surfactant give higher absorbance indicating better dispersion which lead to higher electrical conductivity.

Moreover, in order to determine the stability of the dispersions, zeta potential measurements for MWCNTs-SDS and MWCNTs-CTAB were conducted shown in Figure 7b. Basically, as shown in inset Figure 7b, zeta potential is an electrical potential at slipping plane or at boundary of the double layer which is a technique for the evaluation of the surface charge of nanoparticles including CNTs in a colloidal solution. Here, nanotubes have a charge on the surface that attracts a thin layer of ions to the nanotube surface which is called stern layer [44]. To evaluate this, the surface of MWCNTs was modified by cationic (CTAB) and anionic (SDS) surfactant at a fixed MWCNTs concentration (1 wt.%/v) using sonication technique. From the conducted studies, it is indicated that the magnitude of zeta potential is predictive for the colloidal stability of the dispersion and a zeta potential value greater than ±60 mV indicates that the dispersions have excellent stability [45]. Obtained results show that MWCNTs-CTAB dispersions have peaks at around 71 mV and 72 mV, whereas MWCNTs-SDS dispersions have -101 mV and -96 mV zeta potential values, indicating that the MWCNT have better and more stable dispersion with SDS rather than CTAB due to higher level of zeta potential at same concentration and dispersion parameters. Positive values of MWCNTS-CTAB and negative values for MWCNTs-SDS based dispersions are attributed to the absorption of cationic and anionic charge on the MWCNTs surface [46]. Depending on the nature of the surfactants, cation and anion are forming. Here, surfactants are absorbed in the MWCNTs surface where either positive or negative change result in electrostatic repulsion between the molecules that leads to stabilization of the nanotubes colloids [47].

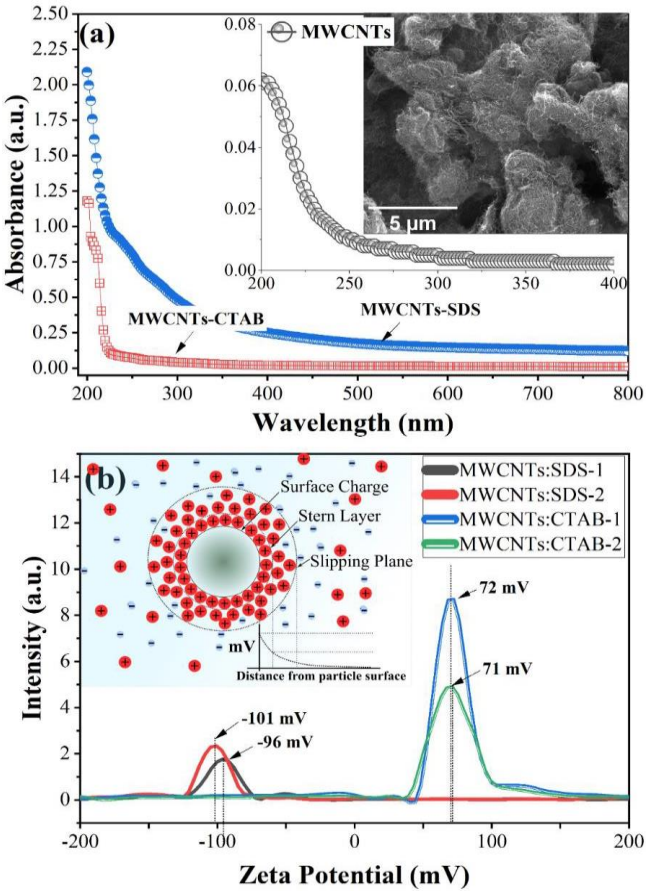

Figure 6. (a) UV-Vis spectra and (b) Zeta potential of MWCNTs-SDS and MWCNTs-CTAB dispersions. Inset figure in (a) shows UV- Vis and SEM image of non-dispersed MWCNTs and (b) shows the basic working principle of zeta potential

Furthermore, MWCNTs-surfactant/TPU nanofibrous structures were examined by FT-IR device to analyze the interface interaction between TPU fibers and dispersed MWCNTs structures. The FT-IR spectrum of the electrospun TPU film, MWCNTs-SDS/TPU and MWCNTs-CTAB/TPU are given in Figure 7a. Here, it is seen that for the electrospun neat TPU fibers, the peak at 3302 cm^{-1} is the characteristic N-H stretching band of the urethane structure, and the peak at 1728 cm^{-1} and at 1699 cm^{-1} are indicative of the free carbonyl group in the urethane bonds (–H–N–COO) and free H bonded C-O bonds respectively. The peaks at 2920 cm^{-1} and 2820 cm^{-1} are characteristics of medium alkenes-CH stretching vibrations. Also, the peak at the wavelength of 1525 cm^{-1} correlates with C–H. In addition, the C–O and C–O–C bands are available at wavelengths of 1219 cm^{-1} and 1074 cm^{-1}, respectively. Peaks at similar wavelengths were also observed in the FT-IR spectrum in the literature [48, 49]. Moreover, the FT-IR spectra of the MWCNTs decorated films match the spectra of the TPU film. It is seen that bathochromic shift (red shift) occurs as the TPU peaks shift

to the right in the coated films. Related studies indicating that the red shift can be attributed to the effects of increasing electron conjugation of conductive and semiconductor materials and the effect of increasing electron conjugation of CNTs [50-52]. Namely, abovementioned shifts indicate strong interactions between TPU chains and MWCNTs that is critical for the enhancement of electromechanical properties of electrospun MWCNTs decorated TPU fibrous structures. Subsequently, to study the effect of different type of surfactants on the electrical properties of electrospun MWCNTs-surfactant/TPU nanofibrous structures were measured by 2-point and 4-point probe resistance measurements given in Figure 7b. From the 2-points probe resistance measurements, it is calculated that electrospun samples based on MWCNTs-SDS/TPU and MWCNTs-CTAB/TPU have a resistance value around 25 kΩ and 31.3 kΩ, respectively. From the 4-point surface resistance measurements these resistance values decreased to 19 kΩ ± 3.52% and 27 kΩ ± 4.79% for MWCNTs-SDS/TPU and MWCNTs-CTAB/TPU samples, respectively. These findings suggest that MWCNTs are better dispersed in SDS surfactant that leads lower resistance values.

Finally, to see the effect of surfactant on the strain sensing characteristics of electrospun nanofibers, samples were undergone to uniaxial loading with the tensile speed of 1 mm/h and relative resistance changes at each strain value were recorded. It is seen that both samples show strain sensitivity with two linear regions. As previously reported [6], the piezoresistive working mechanism of MWCNTs decorated electrospun nanofibers can be explained as follows (see inset Figure 7c). At low strain range (region I) up to 36%, randomly oriented TPU fibers starts to move away from each other that lead to increase in resistance value. With the further increase of uniaxial strain (Region II), the distance between dispersed MWCNTs on the TPU fibers increase that results in a rapid increase in resistance [53]. Up to 50% of tensile strain, the relative resistance change for the MWCNTs-CTAB sample is nearly 264%, this value gets to 292% for the MWCNTs-SDS/TPU sample, which is attributed again a better dispersion of MWCNTs that contributes the piezoresistivity of nanofibrious structure with enhanced sensitivity. Namely, formation of more homogenously dispersed MWCNTs networks enhance the overall relative resistance change under uniaxial applied strain.

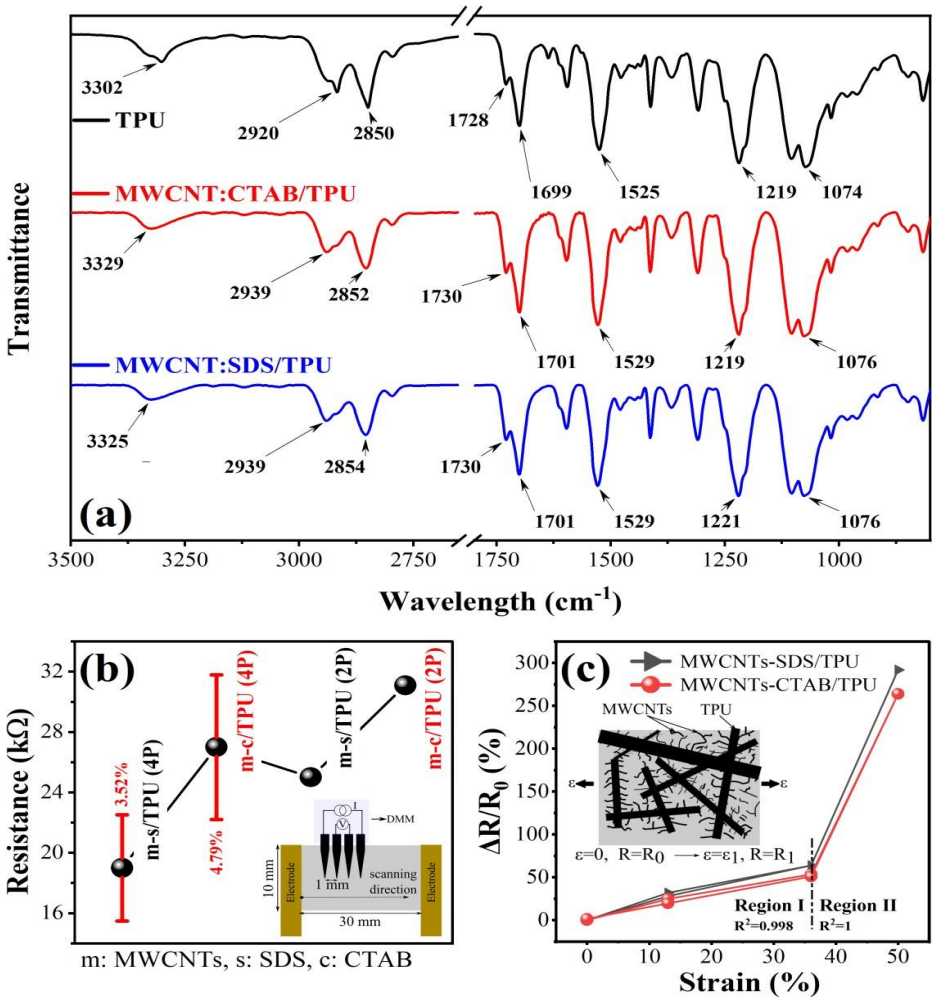

Figure 7. (a) FT-IR Spectra, (b) 2-point and 4-point probe resistance measurements and (c) uniaxial tensile strain measurement of electrospun MWCNTs-SDS/TPU and MWCNTs-CTAB/TPU samples. Inset figure in (b) and (c) shows the measurement setup for 4-point probe resistance measurement and piezoresistive working mechanism of electrospun sample under uniaxial tensile strain

4 CONCLUSION

This study investigates the effect of surfactant type (SDS and CTAB) on the electromechanical properties of MWCNTs decorated flexible electrospun TPU nanofibers. From the morphological investigations of electrospun nanofibers, it is seen that TPU fibers are homogenously distributed and for both surfactant type and slightly better dispersion for MWCNTs-SDS solution based nanofibers were formed. Dispersion characterizations based on UV-Vis and zeta potential analysis also suggest that MWCNTs-SDS solutions have higher absorbance. Zeta potential results showing that MWCNTs dispersion with SDS have higher level of zeta potential than CTAB solutions which leads again better and more stable dispersion. FTIR analysis of the MWCNTs decorated TPU nanofibers shows a shift at peaks that is attributed to increasing electron conjugation of carbon nanotubes. From both 2P and 4P electrical resistance measurement MWCNTs-SDS/TPU samples has lower resistance owing to better dispersion of MWCNTs. Subsequently, from the uniaxial tensile strain measurement, MWCNTs-SDS dispersions decorated electrospun TPU nanofibers give higher sensitivity which is as a consequence of better dispersion of MWCNTs that are responsible for piezoresistivity of nanofibers. Obtained results of this study provide new insights into the tailoring the electromechanical properties of MWCNTs decorated electrospun nanofibers by adjusting the type of the surfactant.

Acknowledgement

This study was funded by The Scientific and Technological Research Council of Turkey (Turkiye Bilimsel ve Teknolojik Arastirma Kurumu- TÜBİTAK) (Grant number 121M137).

REFERENCES

1. Park S, Vosguerichian M, Bao Z. 2013. A review of fabrication and applications of carbon nanotube film-based flexible electronics. *Nanoscale* 5(5), 1727-1752.
2. Sanli A. 2020. Investigation of temperature effect on the electrical properties of MWCNTs/epoxy nanocomposites by electrochemical impedance spectroscopy. *Advanced Composite Materials* 29(1), 31-41.
3. Sanli A, Kanoun O. 2020. Electrical impedance analysis of carbon nanotube/epoxy nanocomposite-based piezoresistive strain sensors under uniaxial cyclic static tensile loading. *Journal of Composite Materials* 54(6), 845-855.
4. Sanli A, Benchirouf A, Müller C, Kanoun O. 2017. Piezoresistive performance characterization of strain sensitive multi-walled carbon nanotube-epoxy nanocomposites. *Sensors and Actuators A: Physical* 254, 61-68.
5. Sanli A, Müller C, Kanoun O, Elibol C, Wagner MFX. 2016. Piezoresistive characterization of multi-walled carbon nanotube-epoxy based flexible strain sensitive films by impedance spectroscopy. *Composites Science and Technology* 122, 18-26.
6. Sanli A, Yildiz K, Uzun M. 2021. Experimental study of the impact of electrospinning parameters on the electromechanical properties of strain sensitive electrospun multiwalled carbon nanotubes/thermoplastic polyurethane nanofibers. *Advanced Composite Materials* 1-16.
7. Kanoun O, Müller C, Benchirouf A, Sanli A, Dinh TN, Al-Hamry A, Bu L, Gerlach C, Bouhamed A. 2014. Flexible carbon nanotube films for high performance strain sensors. *Sensors* 14(6), 10042-10071.
8. Al-Saleh MH, Sundararaj U. 2009. Electromagnetic interference shielding mechanisms of CNT/polymer composites. *Carbon* 47(7), 1738–1746.
9. Sandler JKW, Pegel S, Cadek M Gojny F, Van Es M, Lohmar J, Blau WJ, Schulte K, Windle AH, Shaffer, MSP. 2004. A comparative study of melt spun polyamide-12 fibres reinforced with carbon nanotubes and nanofibres. *Polymer* 45(6), 2001-2015.
10. Narh KA, Jallo L, Rhee KY. 2008. The effect of carbon nanotube agglomeration on the thermal and mechanical properties of polyethylene oxide. *Polymer Composites* 29(7), 809-817.
11. Ma PC, Siddiqui NA, Marom G, Kim JK. 2010. Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review. *Composites Part A: Applied Science and Manufacturing* 41(10), 1345-1367.
12. Vaisman L, Wagner HD, Marom G. 2006. The role of surfactants in dispersion of carbon nanotubes. *Advances in Colloid and İnterface Science* 128, 37-46.
13. Duan WH, Wang Q, Collins F. 2011. Dispersion of carbon nanotubes with SDS surfactants: A study from a binding energy perspective. *Chemical Science* 2(7), 1407-1413.
14. Yook JY, Jun J, Kwak S. 2010. Amino functionalization of carbon nanotube surfaces with NH3 plasma treatment. *Applied Surface Science* 256(23), 6941-6944.
15. Rahman MJ, Mieno T. 2016. Safer production of water dispersible carbon nanotubes and nanotube/cotton composite materials. In Carbon Nanotubes-Current Progress of their Polymer Composites. IntechOpen.
16. Labille J, Pelinovskaya N, Botta C, Bottero JY, Masion A. 2016. Fabrication of Graphene or Graphene Fabrication.
17. Georgakilas V, Otyepka M, Bourlinos AB, Chandra V, Kim N, Kemp KC, Hobza P, Zboril R, Kim KS. 2012. Functionalization of graphene: covalent and non-covalent approaches, derivatives and applications. *Chemical Reviews* 112(11), 6156-6214.
18. Ngo CL, Le QT, Ngo TT, Nguyen DN, Vu MT. 2013. Surface modification and functionalization of carbon nanotube with some organic compounds. *Advances in Natural Sciences: Nanoscience and Nanotechnology* 4(3), 035017.
19. Rausch J, Zhuang RC, Mäder E. 2010. Surfactant assisted dispersion of functionalized multi-walled carbon nanotubes in aqueous media. *Composites Part A: Applied Science and Manufacturing* 41(9), 1038-1046.
20. Syrgiannis Z, Hauke F, Röhrl J, Hundhausen M, Graupner R, Elemes Y, Hirsch A. 2008. Covalent sidewall functionalization of SWNTs by nucleophilic addition of lithium amides. European Journal of Organic Chemistry 2008(15), 2544-2550.
21. Lin Y, Ng KM, Chan CM, Sun G, Wu J. 2011. High-impact polystyrene/halloysite nanocomposites prepared by emulsion polymerization using sodium dodecyl sulfate as surfactant. *Journal of Colloid and Interface Science* 358(2), 423-429.
22. Zhang G, Wang F, Dai J, Huang Z. 2016. Effect of functionalization of graphene nanoplatelets on the mechanical and thermal properties of silicone rubber composites. *Materials* 9(2), 92.

23. Emami Z, Meng Q, Pircheraghi G, Manas-Zloczower I. 2015. Use of surfactants in cellulose nanowhisker/epoxy nanocomposites: effect on filler dispersion and system properties. *Cellulose* 22(5), 3161-3176.

24. Zang J, Wan YJ, Zhao L, Tang LC. 2015. Fracture behaviors of TRGO-Filled epoxy nanocomposites with different dispersion/ınterface levels. *Macromolecular Materials and Engineering* 300(7), 737-749.

25. Shamsuri AA, Md. Jamil SNA. 2020. A short review on the effect of surfactants on the mechanico-thermal properties of polymer nanocomposites. *Applied Sciences* 10(14), 4867.

26. Choudhary M, Kamil SM. 2020. Phase diagram study of sodium dodecyl sulfate using dissipative particle dynamics. *ACS Omega* 5(36), 22891- 22900.

27. Miraç A, Toçuoğlu U, Kayış F, Akbulut H. 2016. Karbon Nano Tüplerin Dispersiyonuna SDS Yüzey Aktif Maddesinin Etkisi. *Bilecik Şeyh Edebali Üniversitesi Fen Bilimleri Dergisi* 3(1), 16-19.

28. Niraula TP, Bhattarai A, Chatterjee SK, Biratnagar N. 2014. Sodium dodecylsulphate: A very useful surfactant for scientific investigations. *Journal of Knowledge and Innovation* 2(1), 111-113.

29. Nnyigide OS, Lee SG, Hyun K. 2019. In silico characterization of the binding modes of surfactants with bovine serum albumin. *Scientific Reports* 9(1), 1-16.

30. Cui H, Yan X, Monasterio M, Xing F. 2017. Effects of various surfactants on the dispersion of MWCNTs–OH in aqueous solution. *Nanomaterials* 7(9), 262.

31. Wang H. 2009. Dispersing carbon nanotubes using surfactants. *Current Opinion in Colloid & Interface Science* 14(5), 364-371.

32. Madni I, Hwang CY, Park SD, Choa YH, Kim HT. 2010. Mixed surfactant system for stable suspension of multiwalled carbon nanotubes. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 358(1-3), 101-107.

33. Rajendran D, Ramalingame R, Adiraju A, Nouri H, Kanoun O. 2022. Role of solvent polarity on dispersion quality and stability of functionalized carbon nanotubes. *Journal of Composites Science* 6(1), 26.

34. Ndiaye AL, Varenne C, Bonnet P, Petit E, Spinelle L, Brunet J, Pauly A, Lauron B. 2012. Elaboration of SWNTs-based gas sensors using dispersion techniques: Evaluating the role of the surfactant and its influence on the sensor response. *Sensors and Actuators B: Chemical* 162(1), 95- 101.

35. Zou B, Chen SJ, Korayem AH, Collins F, Wang CM, Duan WH. 2015. Effect of ultrasonication energy on engineering properties of carbon nanotube reinforced cement pastes. *Carbon* 85, 212-220.

36. Chatterjee S, Castro M, Feller JF. 2015. Tailoring selectivity of sprayed carbon nanotube sensors (CNT) towards volatile organic compounds (VOC) with surfactants. *Sensors and Actuators B: Chemical* 220, 840-849.

37. Schneider CA, Rasband WS, Eliceiri KW. 2012. NIH Image to ImageJ: 25 years of image analysis. *Nature methods* 9(7), 671-675.

38. Kataura H, Kumazawa Y, Maniwa Y, Umezu I, Suzuki S, Ohtsuka Y, Achiba Y. 1999. Optical properties of single-wall carbon nanotubes. *Synthetic Metals* 103(1-3), 2555-2558.

39. Hamada N, Sawada SI, Oshiyama A. 1992. New one-dimensional conductors: Graphitic microtubules. *Physical Review Letters* 68(10), 1579.

40. Saito R, Fujita M, Dresselhaus G, Dresselhaus UM. 1992. Electronic structure of chiral graphene tubules. *Applied Physics Letters* 60(18), 2204-2206.

41. Jiang L, Gao L, Sun J. 2003. Production of aqueous colloidal dispersions of carbon nanotubes. *Journal of Colloid and Interface Science* 260(1), 89-94.

42. Hertel T, Walkup RE, Avouris P. 1998. Deformation of carbon nanotubes by surface van der Waals forces. *Physical Review B* 58(20), 13870.

43. Yu J, Grossiord N, Koning CE, Loos J. 2007. Controlling the dispersion of multi-wall carbon nanotubes in aqueous surfactant solution. *Carbon* 45(3), 618-623.

44. Lee SH, Woo SP, Kakati N, Kim DJ, Yoon YS. 2018. A comprehensive review of nanomaterials developed using electrophoresis process for high-efficiency energy conversion and storage systems. *Energies* 11(11), 3122.

45. Kumar A, Dixit CK. 2017. Methods for characterization of nanoparticles. In Advances in nanomedicine for the delivery of therapeutic nucleic acids (pp. 43-58). Woodhead Publishing.

46. Bai Y, Gao J, Wang C, Zhang R, Ma W. 2016. Mixed surfactant solutions for the dispersion of multiwalled carbon nanotubes and the study of their antibacterial activity. *Journal of Nanoscience and Nanotechnology* 16(3), 2239-2245.

47. de la Cruz EF, Zheng Y, Torres E, Li W, Song W, Burugapalli K. 2012. Zeta potential of modified multi-walled carbon nanotubes in presence of poly (vinyl alcohol) hydrogel. *International Journal of Electrochemical Science* 7(4), 3577-3590.

48. Ren M, Zhou Y, Wang Y, Zheng G, Dai K, Liu C, Shen C. 2019. Highly stretchable and durable strain sensor based on carbon nanotubes decorated thermoplastic polyurethane fibrous network with aligned wave-like structure. *Chemical Engineering Journal* 360, 762-777.

49. Li Y, Zhou B, Zheng G, Liu X, Li T, Yan C, Cheng C, Dai K, Liu C, Shen C, Guo Z. 2018. Continuously prepared highly conductive and stretchable SWNT/MWNT synergistically composited electrospun thermoplastic polyurethane yarns for wearable sensing. *Journal of Materials Chemistry C* 6(9), 2258-2269.

50. Ugraskan V, Karaman F. 2021. Polyaniline/Graphitic carbon nitride nanocomposites with improved thermoelectric properties. *Journal of Electronic Materials* 50(6), 3455-3461.

51. Ugraskan V, Tari E, Yazici O. 2021. Poly (3, 4-Ethylenedioxythiophene): Poly (Styrene Sulfonate)/Boron carbide hybrid composites with improved thermoelectric performance. *Journal of Electronic Materials* 50(10), 5618-5624.

52. Rohlfing M. 2012. Redshift of excitons in carbon nanotubes caused by the environment polarizability. *Physical Review Letters* 108(8), 087402.

53. Wang Y, Hao J, Huang Z, Zheng G, Dai K, Liu C, Shen C. 2018. Flexible electrically resistive-type strain sensors based on reduced graphene oxide-decorated electrospun polymer fibrous mats for human motion monitoring. *Carbon* 126, 360-371.