

ELABORATION OF A NANOCOMPOSITE BASED ON POLYSTYRENE CARBON NANO-TUBES BY ELECTROSPINNINGISSAOUI CH.^{1*}, KHENOUSI N.², HAJSAID A.¹, SCHACHER L.² AND ROUDESLI S.¹¹LABORATORY OF ADVANCED MATERIALS AND INTERFACES, FSM TUNISIA²LABORATORY OF TEXTILE, PHYSICS AND MECHANICS, ENSISA, MULHOUSE, FRANCE*Received 28 October 2015, Accepted 10 November 2016***ABSTRACT**

Electrospinning has been recognized as an efficient technique for the fabrication of polymer and composites nanofiber. Various polymers have been successfully electrospun into ultrafine fibers in recent years mostly in solvent solution and some in melt form. Polystyrene (PS) dissolved in N,N-Dimethyl Formamide (DMF) was electrospun to obtain fibers of diameters in the range of 800nm. The effects of the concentration, voltage and working distance were observed by Scanning Electron Microscopy (SEM). The optimum solution was used to elaborate a composite single-walled carbon nanotubes (CNTs) / polystyrene. We have reached 2% of CNTs in the polymer matrix when adding oligo-para-methoxy-toluene (OPMT). The diameters decreased when using OPMT and reached 600nm and the surface became smoother. The influence of OPMT on the nanofibers' diameters was noteworthy. Diameters attained 2.1 μ m in the case of PS/CNTs (1%). However, in the case of PS/OPMT/CNTs (1%) they expanded to 600nm.

KEYWORDS

Electrospinning; morphology; composite; dispersion; CNTs.

1. INTRODUCTION

Nanotechnology is a rapidly growing multidisciplinary field of research which has attracted the interest of an overwhelming number of researchers around the world. Among nanotechnology, nanofiber technology is one of the most emerging fields (Lu, Ding, 2008). Many methods were used to produce nanofibers such as the technique by electrospinning. Electrospinning is a process transforming solution or melt into submicron fibers by using electrostatic forces (Doshi, Reneker, 1995; Greiner, Wendorff, 2007; Subbiah *et al.*, 2005, Thandavamoorthy *et al.*, 2006). The first electrospinning trials were already made in 1930 and the first patents were issued by Formhals in 1934 (Formhals, 1934). Electrospinning process is capable to produce fibers ranging from 10 nm to a few microns. The advantages of this process are its versatility and technical simplicity. Nanofibers produced by electrospinning can be reinforced to elaborate a composite (Li *et al.*, 2006, Tamer *et al.*, 2009; Huang *et al.*, 2003). Carbon nanotubes are currently of a large interest to elaborate nanocomposite. In fact, since their discovery by Iijima, carbon nanotubes (CNTs) have attracted the attention of researchers because of their unique structure and extraordinary physical properties (Iijima, 1991). Carbon nanotubes, and particularly single-walled carbon nanotubes (SWNTs), are excellent reinforcing materials for a variety of matrices (Zaidi *et al.*, 2010; Song *et al.*, 2007; Rahul *et al.*, 2004).

However, CNTs presented many difficulties in their processing and dispersion. Bulk production of CNTs often results in a dense entangled network of nanotube bundles. Thus, their dispersion, and their alignment are elementary crucial steps for several useful applications (Haj Said *et al.*, 2011, Peng-Cheng *et al.*, 2010, Huang and Terentjev, 2008 and 2012).

* Corresponding author. Email : issaoui_chafia@yahoo.fr

Many studies use the electrospinning technique to improve nanoparticle dispersion (Doshi, Reneker, 1995, Ge *et al.*, 2004). The apparatus of electrospinning consists of a high voltage electric source with positive or negative polarity, a syringe or pipette feeding the solution by means of a syringe pump, and a conducting collector like aluminum. The small diameter of fibers is the specific characteristic of this process. The produced nanofibers have many fields of applications such as nanofiltration, nanosensors (Dajing *et al.*, 2011), Tissue Engineering Scaffolding and photovoltaic devices (Huang *et al.*, 2003).

A problem still remains in the electrospinning technique, which is the unstable deposition of the fiber resulting in the production of non-woven fabrics. These fabrics have varying characteristics and many studies have been conducted to solve this problem by making the fiber deposition controllable (Teeradech *et al.*, 2005).

In this paper we study the effect of some parameters on nanofiber morphology. We report, firstly, the experimental condition optimization to elaborate a polystyrene nanofiber. Secondly, we elaborate nanofibers of polystyrene/carbon nanotubes (PS/ CNTs) and polystyrene/ oligo-para-methoxy-toluene/ carbon nanotubes PS/OPMT/CNTs to reveal how OPMT could functionalize CNTs and produce their dispersion.

2. EXPERIMENTALS

2.1. Materials

Polystyrene of a molecular weights 280000, purchased from Aldrich Chemicals.

N, N-dimethyl formamide (DMF) purchased from FLUKA.

Para-methoxy-toluene was provided by ACROS.

OPMT: were prepared in our laboratory (Said *et al.*, 2000). The following experimental protocol was adopted: in a nonseparated cell containing both a working electrode (16cm² platinum grid) and the counter electrode (4 cm² platinum grid), galvanostatic electrolyses were carried out on 5 g of para-methoxy-toluene. A Tacussel PRT 1-100 potentiostat and an IG-5N current integrator were used. The solution was homogenized by ultrasonic Bransonic 220 bath (48 kHz). The electrolysis solutions were extracted with chloroform. Then the polymer was precipitated successively in methanol, diethyl ether, and finally in cyclohexane. Our study is focused on the shorter chain oligomer precipitated in cyclohexane.

The single-walled carbon nanotubes (SWNTs) powder with the following properties (diameter: 1.2-1.5 nm, length: 2-5 μ m, density: 1.7-1.9 g/mL)

2.2. Electrospinning set up

The electrospinning setup consists of a high-voltage power supply, a syringe pump and a collector, as shown in Figure 1. The polymer solution was fed into a syringe pump so that the flow rate of the solution could be controlled. Nanofibers were collected on an aluminum collector. The needle with a diameter of 0.7 mm was electrically connected to a positive high-voltage power source delivering a potential maximum of 30KV.

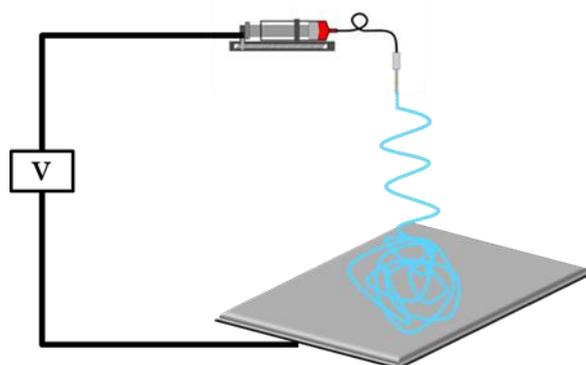


Figure 1: Electrospinning set up

2.3. Solution Preparation

2.3.1. Polystyrene solution

A series of experiments were carried out using polystyrene. The weight percentage varied from 10% to 35%. The working distance was held from 10 to 25cm and the applied voltage varied from 10 to 25KV. Table 1 describes different experiment conditions.

Table 1: Different experiment conditions

Concentration	Voltage (KV)	Work Distance
15wt%	10	10
	15	15
	20	20
	25	25
20wt%	10	10
	15	15
	20	20
	25	25
25wt%	10	10
	15	15
	20	20
	25	25
30wt%	10	10
	15	15
	20	20
	25	25
35%	10	10
	15	15
	20	20
	25	25

2.3.2. Preparation of blend solution

A series of experiments were carried out on PS/CNTs (1%), PS/OPMT/CNTs (1%, 2%) and PS/OPMT using DMF as solvent.

CNTs and CNTs/OPMT were dispersed using an aqueous ultrasonic bath for 30mn.

When the solution of CNT or CNT/OPMT became homogenous, we added polystyrene solution to obtain homogenized solution with a concentration of 25wt%.

2.4. Characterisation of the Electrospun fibres

Fiber morphology of the electrospun polystyrene webs were determined using a scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

3.1. Operatory condition optimization

3.1.1. Concentration Influence

The concentration of the polymer has a major effect in electrospinning. In fact, when its concentration is too high or too low, electrospinning becomes impossible. We have chosen five concentrations 10, 15, 20, 25 and 30 wt%.

In the case of 10% it was impossible to do electrospinning. However, when increasing the concentration, it became more regular until we reached a maximum value and the electrospinning was no more possible.

For a low concentration (10%), electrospinning was impossible because the solution was diluted. In fact, polymer chain entanglements decreased significantly. As for the process of electrospinning, the polymer chains in the solution were transformed into oriented entangled networks by the elongation flow of the jet.

So, a minimum of chain entanglement is required to form fibers. Below this critical chain entanglement, we obtain beads and fibers because of jet instability. Figure 2 shows the SEM micrographs of different concentrations. With a concentration of 15% (figure 2 (a)) electrospinning is possible but as it is shown in SEM micrographs the structure presented many beads due to jet instability.

However, for a concentration of 20% (figure 2 (b)) the structure is more regular when varying voltage or distance. With a concentration of 25% (figure 2 (c)) the structure is regular when varying voltage or distance but not in all cases. However, for a concentration of 30% (figure 2 (d)) the structure is regular in all cases but with larger diameters.

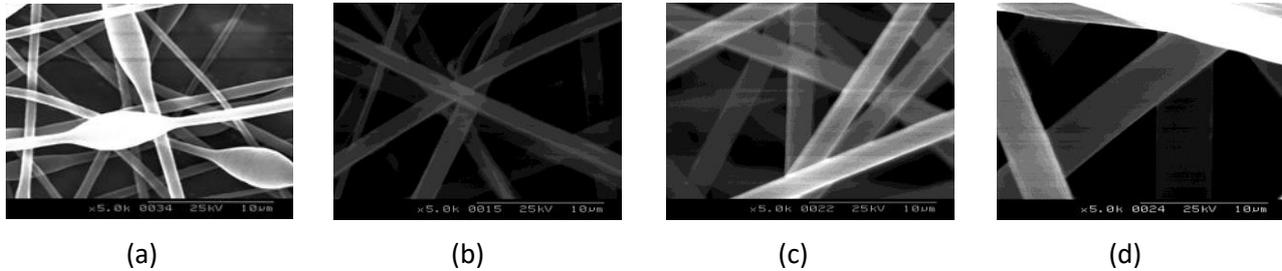


Figure 2: SEM photographs of PS fibers produced from different concentrations (a) 15%, (b) 20%, (c) 25% and (d) 30%. The solvent, applied voltage and distance were DMF, 20 kV, 20 cm, respectively.

To conclude we can say that the concentration of polymer solution plays an important role in fiber structure. We can distinguish four critical concentrations from low to high.

At a very low concentration; we obtain polymer particle and we have electro spray phenomena instead of electrospinning. When increasing the concentration a little bit; we obtain a mixture of beads and fibers. For a suitable concentration; we obtain smooth and regular nanofibers. However, when increasing the concentration a little higher, we obtain micro-ribbons.

When increasing the concentration of the solution, the fiber diameter increases. So, it is important to reach the suitable concentration in order to obtain nanofibers with less diameters.

3.1.2. Voltage Influence

In this section, we have fixed distance to 20cm and we have varied concentration from 15% to 30% and voltage from 10KV to 25KV. Figure 3 shows the SEM micrographs and the surface morphology of the obtained fibers when using a concentration of PS that equals 15%. Spindle-like beads were formed in all varying values of voltage.

The number of the beads decreases when increasing voltage and their form changes (Lee et al., 2003). At low voltage, the beads forms are almost spherical (fig. 3 (a)) and they were becoming more and more elliptic as we increased voltage (fig. 3 (c)). At the highest value of voltage used (25 KV) the form became almost elliptic (fig. 3 (d)).

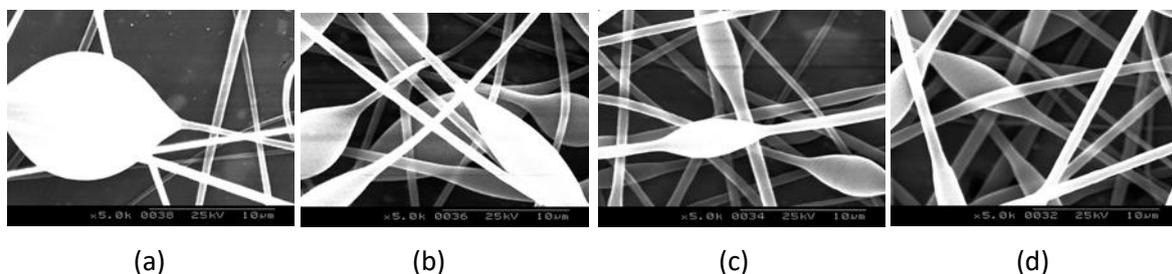


Figure 3: SEM photographs of PS fibers produced by applying different voltages (a) 10KV, (b) 15KV (c) 20KV and (d) 25KV. The solvent, concentration and distance were DMF, 15%, 20 cm, respectively

The following SEM micrographs presented in Figure 4 show the surface morphology of the obtained fibers when using a concentration of 20%, at a distance of 20cm and voltage varying from 10KV to 25KV.

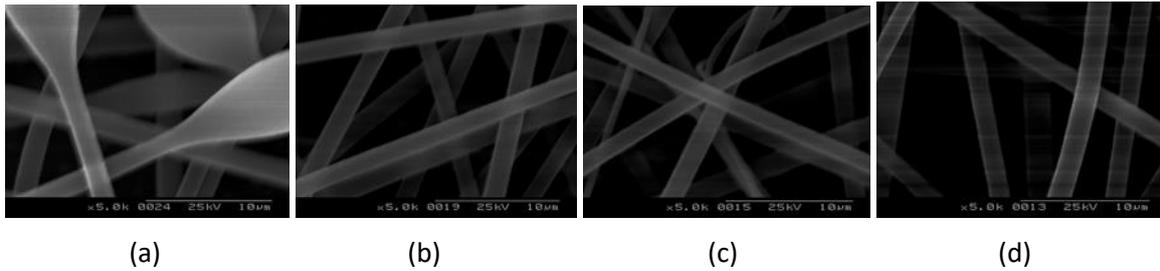


Figure 4: SEM photographs of PS fibers produced by applying voltages (a) 10KV, (b) 15KV (c) 20KV and (d) 25KV. The solvent, concentration and distance were DMF, 20%, 20 cm, respectively

For a concentration of 20%, we have fixed distance to 20cm and varied voltage. As a result, the obtained nanofibers were relatively smooth and uniform. When increasing voltage, the diameter decreases and the nanofibers become more regular and similar to the literature. (Kwangsok et al., 2005).

In the case of a low voltage of 10KV the structure presented many beads. A voltage too low, below the critical limit, creates electrospray because there is not enough charge to control the instability caused by surface tension. However, when the voltage was increased, the fiber became rougher and the diameter decreased and reached a mean of 1.25µm.

When increasing concentration to 25% we observe the same thing as for a concentration of 20%: beads at 10KV (fig.5 (a)) and regular and uniform structure for other voltages. Diameters ranged from 1.5 to 2.5µm and the structure is almost regular. (fig.5 (b, c and d))

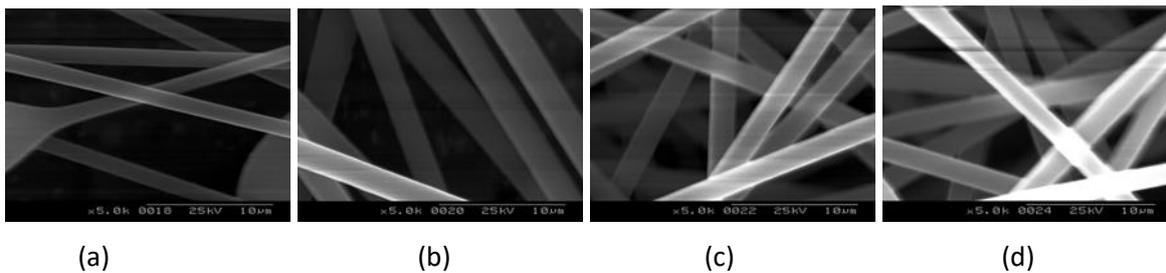


Figure 5: SEM photographs of PS fibers produced by applying different voltages (a) 10KV, (b) 15KV (c) 20KV and (d) 25KV. The solvent, concentration and distance were DMF, 25%, 20 cm, respectively

As it is shown for 25% concentration of PS, the obtained nanofibers are relatively smooth and uniform with a diameter of 1.5µm. When increasing the concentration to 30% (figure 6), we obtain the most regular and uniform structure whatever the voltage. However, in this case the diameters are the largest ranging from 2µm to 5µm.

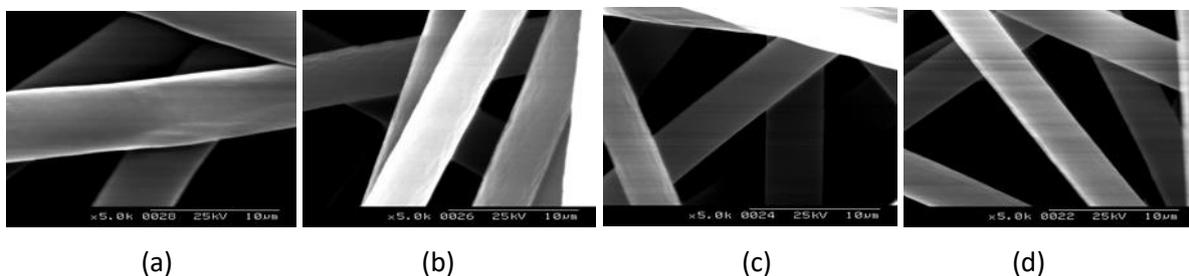


Figure 6: SEM photographs of PS fibers produced by applying different voltages (a) 10KV, (b) 15KV (c) 20KV and (d) 25KV. The solvent, concentration and distance were DMF, 30%, 20 cm, respectively

Within the electrospinning process, the applied voltage is the most crucial factor. Thus, we can conclude that voltage does influence the diameter of the produced fibers, but the level of significance varies with the polymer solution concentration and it depends on the distance between the tip and the collector.

3.1.3. Working Distance Influence

In this part, we have fixed voltage to 20KV and we have varied concentration and distance.

For a constant concentration of 15% (figure 7) in all cases, the structure presented many beads due to the low viscosity of the solution. The shape of beads changes when increasing distance. Indeed, for a work distance of 10cm or for a large distance of 25 cm the ratio of beads increases significantly. In fact, a working distance too short leaves less time for evaporation of the solvent. On the other hand, a collector too far induces a low field and does not have enough strength to attract the jet charge.

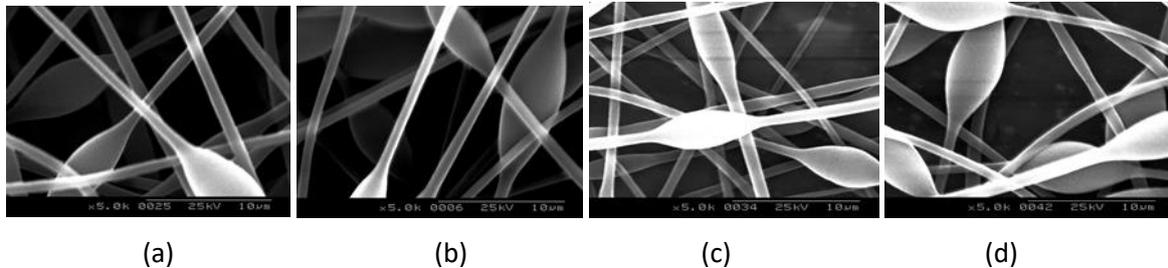


Figure 7: SEM photographs of PS fibers produced at different working distances (a) 10cm, (b) 15cm (c) 20cm and (d) 25cm. The solvent, concentration and voltage were DMF, 15%, 20KV, respectively

For a concentration of 20% with low distance and a high voltage, diameters decrease but are neither regular nor uniform (figure 8 (a, b)). However, when increasing distance the structure is more regular and diameters are uniform (figure 8 (c, d)). In fact, for a constant voltage, the closer the collector is, the more intense the field gets. This could be explained by the fact that the attractive force of the jet charge becomes stronger and therefore the acceleration is higher too.

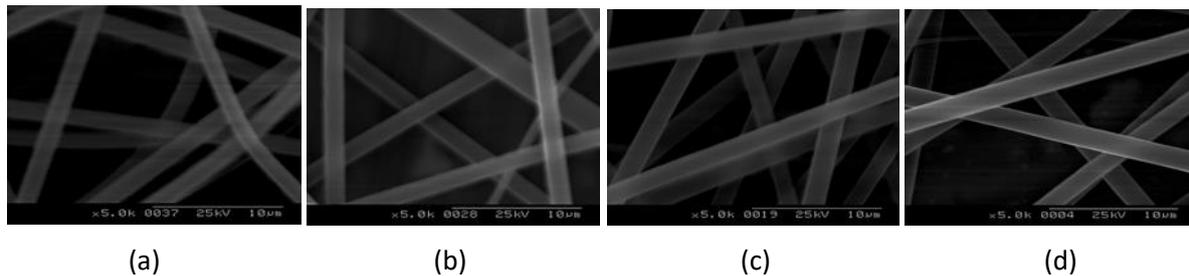


Figure 8: SEM photographs of PS fibers produced at different working distances (a) 10cm, (b) 15cm, (c) 20cm and (d) 25cm. The solvent, concentration and voltage were DMF, 20%, 20KV, respectively

For a concentration of 25% and 30% (fig.9 and 10), we always have regular and uniform fibers due to the high viscosity of the solution. However, when fixing the voltage to 20KV and varying the distance, the fibers diameters show almost no change especially when using the higher concentration.

For 25%, the diameters ranged from 800nm to 2500nm. We reached an optimum for a distance of 25cm and a voltage of 20KV. However for a concentration of 30%, the diameters ranged from 2.5µm to 5µm.

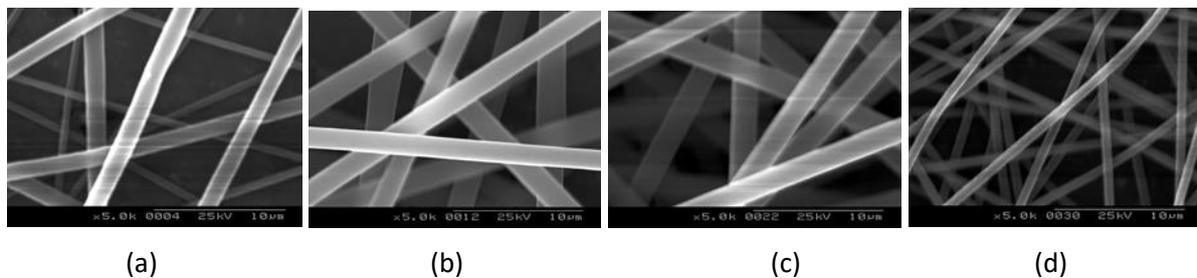


Figure 9: SEM photographs of PS fibers produced at different working distances (a) 10cm, (b) 15cm (c) 20cm and (d) 25cm. The solvent, concentration and voltage were DMF, 25%, 20KV, respectively

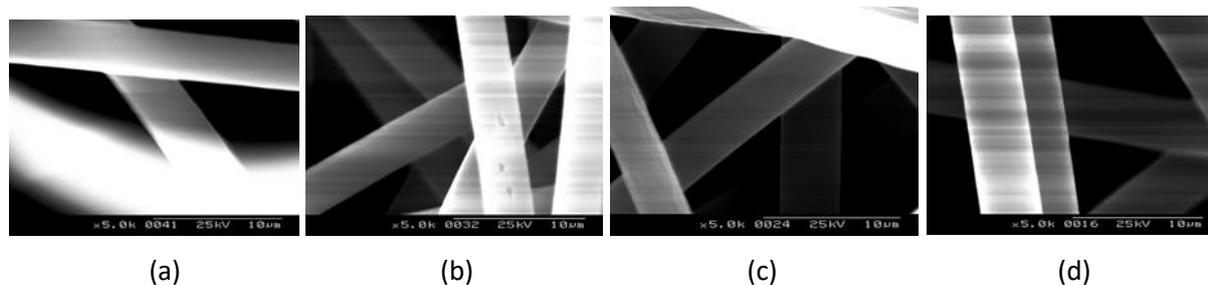


Figure 10: SEM photographs of PS fibers produced at different working distances (a) 10cm, (b) 15cm (c) 20cm and (d) 25cm. The solvent, concentration and voltage were DMF, 30%, 20KV, respectively

It has been proved that the distance can also affect the fiber diameter and morphology (Jarusuwannapoom et al., 2005). In brief, when the distance is too short, the fiber does not have enough time to solidify, whereas if the distance is too long, bead fibers appear. It is well known that dryness of the solvent has an important effect in the physical aspect of the electrospun fiber; thus an optimum distance is recommended (Yuan et al., 2004).

3.1.4. Optimum condition

PS fibers have been successfully prepared by electrospinning using different levels of concentrations. It has been noticed that the morphology of the formed webs was strongly affected by the applied voltage, polymer concentration and working distance. Beads forms changed and decreased when increasing voltage. We reached an optimum concentration of 25%, a voltage of 20KV and a working distance of 25cm. In this operatory condition the diameter equals 800nm. This condition will be used to prepare the blend.

3.2. Nano-composite elaboration

3.2.1. CNTs functionalization

The CNTs assisted dispersion by the oligomer and the strong interaction observed by optical measurements and infrared can suggest a non-covalent functionalization. Indeed, it has been shown that the OPMT can perform supramolecular interactions. This oligomer can probably be absorbed on the level of the surface of the CNTs and by consequence facilitate their dispersion in the same way as pyrene and its derivatives (Yan et al., 2010; Delamar et al., 1992, haj said et al., 2011).

Nevertheless, the dispersion of the CNTs by covalent interaction is not excluded. It is commonly accepted as aromatic radicals can bind covalently to atoms of a carbon electrode during the reduction of the diazonium salts (Bourdillon et al., 1992). Moreover, the CNTs have been functionalized recently (Bahr et al., 2001). These results confirm that the carbon in its graphite form, fullerenes, or NTC is reactive with aromatic radicals. In addition, methods of covalently grafting the polymer radical on the carbon nanotubes or fullerenes have recently been studied (Homenick et al., 2007; Lou et al., 2004; Okamura et al., 1997).

In this study, the oligomer was obtained in the doped state resulting from electrochemical oxidation of para-methoxy-toluene. Delocalization of electrons through the polyphenylene backbone allows for free radical reactivity. Thus, the oligomer radical cation can bind to the surface of the CNTs. This radical reactivity can be enhanced by sonication and cavitation effects, thus generating very high temperature and pressure. Then a covalent bind was established between OPMT and CNTs. A loss of a proton led to the functionalization of CNT. The generated electron can be stabilized by delocalization on the CNTs skeleton or may react with another oligomer chain in a similar manner. Finally, covalent and non-covalent functionalization can be simultaneously involved.

3.2.2. PS/CNTs nanofibers produced by electrospinning

In this study, we have succeeded to elaborate nanofibers from PS/CNTs (1%). Figure 11 shows the SEM micrographs and the surface morphology of obtained fibers. It is shown that for 1% of CNTs nanofibers were regular and homogeneous.

The surface is smooth and there are no beads or irregularity. The diameters have an average width of 2.1 μ m. However, when increasing CNTs in polystyrene matrix the structure is no more homogeneous and the electrospinning is impossible.

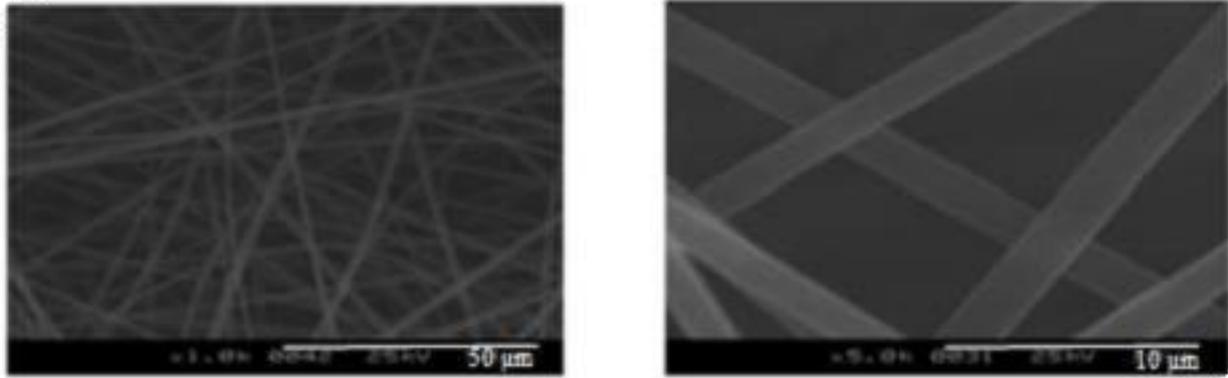


Figure 11: SEM photograph of PS/CNTs (1%) fibers produced from a concentration of 25wt%. The solvent, applied voltage and distance were DMF, 20 kV, 25 cm, respectively

3.3. PS/CNTs/OPMT nanofibers produced by electrospinning

In this part we have prepared nanofibers from PS/OPMT/CNTs using the OPMT as a dispersant (haj said et al., 2011). We succeeded to elaborate nanofibers where CNTs were well dispersed. And we have reached 2% of CNTs in the matrix of polymer.

Figure 12 (a) shows PS/OPMT/CNTs with 1% of CNTs. When compared to figure 11 which is in the same conditions but without OPMT we can conclude that OPMT not only disperses CNTs in a good and regular way but also provides nanofibers with lower diameters and smoother surfaces. In fact, diameters decreased considerably after adding OPMT. It increased from 2.1 μ m in the case of PS/CNT to 600 nm in the case of PS/OPMT/CNT.

Solution conductivity is an important parameter which affects directly fibers size (Tamer, Besenbacher 2008). Solution conductivity is mainly affected by the polymer type, solvent sort, and salt. Usually, conductor polymers are polyelectrolyte so they affect directly the solution conductivity.

Indeed, a solution having high conductivity is subject to higher tension under the electric field. With the aid of conductor polymers, nanofibers with small diameter can be obtained.

At times, high solution conductivity can be also attained by using organic acid as the solvent. For example, Huang et al. used formic acid as the solvent to dissolve the nylon and obtained ultrathin electrospun nylon-beaded fibres (Huang et al., 2006). They added a small amount of pyridine into the solution which increases its conductivity, thus eliminating the beads.

All the data mentioned above indicate that increase in the solution conductivity favours the formation of thinner fibers. However, higher conductive solutions could cause jet instability in the presence of strong electric fields, which then leads to bending and causes instabilities in a wide distribution of nonwoven fibers. While insulation solutions such as paraffin oils provide a relatively stable jet and produce nanofiber that is fairly homogeneous (Demir et al., 2002).

Diameters of fibers decreased considerably when adding OPMT to the matrix polymer. It passed from 1.5 μ m to 500nm respectively in the cases of PS/CNTs (1%) and PS/OPMT/CNTs (1%).

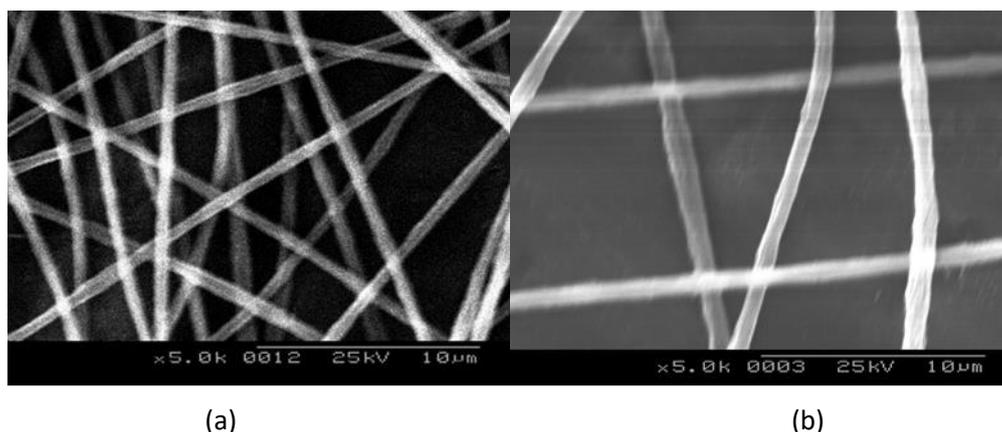


Figure 12: SEM photographs of PS/OPMT/CNTs fibers produced with (a) 1% CNTs, (b) 2% CNTs. The concentration is 25wt%. The solvent, applied voltage and distance were DMF, 20 kV, 25 cm, respectively.

4. CONCLUSION

Polystyrene fibers have been successfully prepared by electrospinning using different concentrations. The morphology of the formed webs was strongly affected by the applied voltage, polymer concentration and working distance. The beads forms changed and decreased when increasing voltage. We reached an optimum concentration of 25%, a voltage of 20kV and a working distance of 25cm. in this operatory condition the diameter of the obtained PS fibers is 800nm.

This study reveals that OPMT is a good candidate for hosting SWNTs and nano-composite elaboration. Moreover, the presence of OPMT causes a good dispersion and produces regular nanofibers with smooth surface. Diameters of the fibers in the case of PS/CNTs (1%) were almost 2.1µm. However, when adding OPMT diameters decreased and reached 600nm. This could be explained by the presence of OPMT as a conducting polymer.

REFERNCES

- Bahr, J. L., Yang, J., Kosynkin, D. V., Bronikowski, M. J., Smalley, R. E., Tour, J. M.(2001).** Functionalization of carbon nanotubes by electrochemical reduction of aryl diazonium salts: a bucky paper electrode. *J Am Chem Soc*, Vol.123, 6536-6542.
- Bourdillion, C., Delamar, M., Demaille, C., Hitmi, R., Moiroux, J., Pinson, J. (1992).** Immobilization of glucose oxidase on carbon surface derivatized of electrochemical reduction of diazonium salts. *J. Electroanal. Chem*, Vol.336, 113-123.
- Dajing, C., Lei, S., Chen, Y. (2011).**A Single Polyaniline Nanofiber Field Effect Transistor and Its Gas Sensing Mechanisms. *Sensors*, Vol.11, 6509-6516.
- Delamar, M., Hitmi, R., Pinson, J., Savéant, J. M.(1992).** Covalent Modification of Carbon Surfaces by Grafting of Functionalized Aryl Radicals Produced from Electrochemical Reduction of Diazonium Salts. *J Am ChemSoc*, Vol.114, 5883-5884.
- Demir, M.M., Yilgor, I., Yilgor, E., Erman B. (2002).**Electrospinning of polyurethane fibers. *Polymer*, Vol.43, 3303-3309.
- Doshi, J., Reneker, D.H.(1995).** Electrospinning Process and Applications of ElectrospunFibers. *Journal of Electrostatics*, Vol.35, N° 2., 151-160.
- Formhals, A.** "Process and apparatus for preparing artificial threads. US Patent, 1975504."
- Ge, J.J., Hou, H., Li, Q., Graham, M.J., Greiner, A., Reneker, D.H., Harris, F.W., Cheng, S.Z. (2004).** Assembly of well-aligned multiwalled carbon nanotubes in confined polyacrylonitrile environments: electrospun composite nanofiber sheets.*J Am Chem Soc*, Vol.126, N°48., 15754-15761.

- Greiner, A., Wendorff, J.H. (2007).** Electrospinning: A Fascinating Method for The Preparation Of Ultrathin Fibres. *Angewandte Chemie-International Edition*, Vol.46, N°30., 5670-5703.
- Haj Said, A., Ayachi, S., Issaoui, Ch., Wéry, J., Alimi, K.(2011).** Optical and Vibrational Studies on Single Walled Carbon Nanotubes/Short Oligo-Para-Methoxy Toluene Composite. *Journal of Applied Polymer Science*, Vol.122, 1889-1897.
- Homenick, C.M., Lawson, G., Adronov, A. (2007).** Polymer grafting of carbon nanotubes using living free-radical polymerization. *Polym Rev*, Vol. 47, 265–290.
- Huang, C., Chen, S., Lai, C., Reneker, D.H., Qiu, H., Ye, Y., Hou, H. (2006).** Electrospun polymer nanofibres with small diameters. *Nanotechnology*, Vol.17, N°6., 1558–1563. doi:10.1088/0957-4484/17/6/004.
- Huang, Y.Y., Terentjev, E.M. (2012).** Dispersion of Carbon Nanotubes: Mixing, Sonication, Stabilization, and Composite Properties. *Polymers*, Vol.4, 275-295; doi:10.3390/polym4010275
- Huang, Y.Y., Terentjev, E.M., (2008).** Dispersion and rheology of carbon nanotubes in polymers. *Int. J. Mater. Form*, Vol.1, 63-74.
- Huang, Z.M., Zhang, Y.Z., Kotakic, M., Ramakrishna, S. (2003).** A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Composites Science and Technology*, Vol.63, 2223–2253. DOI: 10.1016/S0266-3538(03)00178-7.
- Iijima, S. (1991).** Helical microtubules of graphitic carbon. *Nature*, Vol.354, 56-58.
- Jarusuwannapoom, T., Walaiporn, H., Sujinda, J., Ladawan, W., Manit, N., Cattaleeya, P., Piyawit, K., Ratthapol, R., Pitt, S.(2005).** Effect of solvents on electro-spinnability of polystyrene solutions and morphological appearance of resulting electrospun polystyrene fibers. *European Polymer Journal*, Vol.41, 409–421.
- Kwangsook, K., Kang, M., Chin, I.J., Jin, H.J. (2005).** Unique Surface Morphology of Electrospun Polystyrene Fibers from a N,N-Dimethylformamide Solution. *Macromolecular Research*, Vol.13, 533-537.
- Lee, K.H., Kim, H.Y., Bang, H.J., Jung, Y.H., Lee, S.G. (2003).** The change of bead morphology formed on electrospun polystyrene fibers. *Polymer*, Vol.44, 4029–4034, DOI:10.1016/S0032-3861(03)00345-8
- Li, M., Guob, Y., Weib, Y., MacDiarmid, A. G., Lelkes, P. I. (2006).** Electrospinning polyaniline-contained gelatin nanofibers for tissue engineering applications. *Biomaterials*, Vol.27, 2705–2715.
- Lou, X., Detrembleur, C., Sciannamea, V., Pagnouille, C., Jérôme, R.(2004).** Grafting of alkoxyamine end-capped (co) polymers onto multi-walled carbon nanotubes. *Polymer*, Vol.45, 18, 6097-6102.
- Lu, P., Ding, B. (2008).** Applications of Electrospun Fibers. *Recent Patents on Nanotechnology*, Vol.2, 169-182.
- Okamura, H., Terauchi, T., Minoda, M., Fukuda, T., Komatsu, K., (1997).** Synthesis of 1,4-Dipolystyryldihydro[60]fullerenes by Using 2,2,6,6-Tetramethyl-1-polystyroxypiperidine as a Radical Source. *Macromolecules*, Vol.30, 5279-5284.
- Peng-Cheng, M., Naveed, A., Siddiqui, G.M., Jang-Kyo, K.(2010).** Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review, Composites Part A. *Applied Science and Manufacturing*, Vol.41, N° 10., 1345–1367.
- Rahul, S., Bin, Z., Daniel, P., Mikhail, E., Itkis, H., James L. , Elena B., Robert C. H. (2004).** Preparation of Single-Walled Carbon Nanotube Reinforced Polystyrene and Polyurethane Nanofibers and Membranes by Electrospinning. *Nano Letters*, Vol.4, N° 3., 459–464. DOI: 10.1021/nl035135s.
- Said, A. H., Dridi, C., Roudesli, S., Mhalla, F. M.(2000).** Electrochemical synthesis of a polyphenylene deriving from p-methoxytoluene. *Eur Polym Mater*, Vol.36, N°5., 909-914.
- Song, L., Zhang, H., Zhang, Z., Xie, S. (2007).** Processing and performance improvements of SWNT paper reinforced PEEK nanocomposites. *Composites A*, Vol.38, N°2, 388–392

- Subbiah, T. G., Bhat, S., Tock R.W. (2005).**Electrospinning of Nanofibers. *Journal of Applied Polymer Science*, Vol.96, 557–569, DOI: 10.1002/app.21481.
- Tamer, U., Besenbacher, F. (2008).** Electrospinning of uniform polystyrene fibers: The effect of solvent conductivity. *Polymer*, Vol.49, 5336–5343, DOI:10.1016/j.polymer.2008.09.025.
- Tamer, U., Hacaloglu, J., Besenbacher, F.(2009).**Electrospun polystyrene fibers containing high temperature stable volatile fragrance/flavor facilitated by cyclodextrin inclusion complexes. *Reactive & Functional Polymers*, Vol.69, 145–150, DOI:10.1016/j.reactfunctpolym.2008.12.012.
- Teeradech, J., Walaiporn, H., Sujinda, J.,Pitt, S. (2005).**Effect of solvents on electro-spinnability of polystyrene solutions and morphological appearance of resulting electrospun polystyrene fibers. *European Polymer Journal*, Vol.41, 409–421, DOI:10.1016/j.eurpolymj.2004.10.010.
- Thandavamoorthy, S.N., Gopinath, S.N., Ramkumar, S.S.(2006).** Self-Assembled Honeycomb Polyurethane Nanofibers. *Journal of Applied Polymer Science*, Vol.101, 3121–3124.
- Yan, Y., Cui, J., Potschke, P., Voit, B.(2010).**Dispersion of pristine single-walled carbon nanotubes using pyrene-capped polystyrene and its application for preparation of polystyrene matrix composites. *Carbon*, Vol.48, N° 9, 2603-2612.August. doi:10.1016/j.carbon.2010.03.065.
- Yuan, X., Zhang, Y., Dong, C., & Sheng, J. (2004).** Morphology of ultrafine polysulfone fibers prepared by electrospinning. *Polymer International*, 53(11), 1704-1710., doi:10.1002/pi.1538 .
- Zaidi, B., Bouzayen, N., Wéry, J., Alimi, K. (2010).**Grafting of oligo-N-vinyl carbazole on single walled carbon nanotubes. *JMolStruct*, Vol. 971, 71-77.