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SMART TEXTILES INCORPORATING MONOFILAMENTS WITH CARBON NANOTUBES

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KEYWORDS

Carbon nanotubes, Polymer composites; Smart textiles; Smart fabrics; Mechanical properties, Electrical properties.

ABSTRACT

The aim of the work was to contribute to the production of multifunctional textile products, developing polymer matrix composite monofilaments incorporating carbon nanotubes (CNT), to be used as sensors. The carbon nanotube polymer composite (CPC) monofilaments, produced with the required electrical and mechanical properties, were incorporated in textiles, for the development of textile sensors for temperature, pressure, humidity, different gases and solvents. The monofilaments selected for the sensing applications were incorporated directly into the fabrics or by sewing or embroidery.
A multifunctional textile prototype, incorporating sensors and connectors, was produced with the CPC monofilaments developed.

INTRODUCTION

Since their discovery in 1991, CNT have been showing potential for application in numerous fields of science and engineering. The superlative mechanical, thermal and electronical properties attributed to them was never observed in previous materials. The combination of properties makes them ideal candidates as advanced filler materials in composites. Researchers have envisaged taking advantage of their conductivity and high aspect ratio to produce conductive plastics with low percolation thresholds (Kilbride et al. 2002). In another area, it is thought that their massive thermal conductivity can be exploited to make thermally conductive composites (Biercuk et al. 2002). The diameter of the CNT varies from 1 to 100 nm and its length may reach the millimeter scale (Hata et al. 2004). Their densities can be as low as 1.3 g/cm^3 and their Young's moduli are superior to all carbon fibres with values nearn 1 TPa (Wong et al. 1997). Its strength reaches values of 63 GPa (Yu et al. 2000).

In order to provide people with personalized healthcare, technological advances should be brought closer to the subject by means of easy-to-use wearable interfaces between devices and human (Billinghnest and Stamer 1999). A healthier daily life, safer and more comfortable is possible thanks to through multifunctional fabrics. Textiles are being developed in numerous types with various functions. As a result the so-called smart fabrics or e-textile are under development. The final result is expected to be a smart human-machine interface.

The e-textiles are usually separated in two groups. In the first group, there are the transducers and circuit components attached off-the-shelf on fabrics (Post and Orth 1997; Parker et al. 2002; Luthy et al. 2003; Webber et al. 2003; Jung et al. 2003; Park et al. 2002). As an example, a research team from the University of Southern California, Virginia Tech and Raytheon has developed an acoustic beamforming array on textiles. They used a textile fiber network in fabric containing discrete microphones (Parker et al. 2002). In the second group are the conductive yarns, conventional yarns modified with various functional materials, conducting polymers or carbon fiber, are flexible materials developed to incorporate electronics and transducer yarns (Tao et al. 2000; De Rossi et al. 1999; El-Sherif et al. 2000; Catrysse et al. 2003).

EXPERIMENTAL

The major tasks of the project comprised the production and characterization of CNT monofilament composites with different polymer matrices.

The polymers chosen for the composite production were PLA, PP, TPU and a blend of PP and PCL. The overall CNT composition was 4%, except for the PP/PCL blend in 50:50 proportion, were the 4%CNT were dispersed in the PCL fraction originating filaments with overall 2% CNT.

The CNT composites were active for different sensing applications, namely:

- Liquid water sensing: PLA / 4% CNT;
- Strain sensing: TPU / 4% CNT;
- Temperature sensing: 50%PP/50% (PCL/4%CNT).

Materials

The materials used for the production of carbon/polymer composites (CPC) for monofilament and multifilament yarns are detailed in Table 1.

Table 1: CPC Prepared by Twin-screw Extrusion

Masterbatch	**Origin**	**CPC prepared**
CNT N7000	Nanocyl	-
PLA/17% CNT	Nanocyl	Produce PLA/4% CNT by dilution with PLA
TPU/5%CNT	Nanocyl	Prepare TPU/4% CNT by dilution with TPU
PP H777-25R	DOW	PP(50%) + PCL/CNT4% (50%)
PCL/4% CNT	Nanocyl	

Equipment and experimental procedures

Preparation of the CPC composites

The PLA/4% CNT composite was prepared by melt processing, diluting the PLA/CNT masterbatch on a Coperion ZSK 27 MEGACOMPOUNDER modular co-rotating twin screw extruder fitted with the adequate screw configuration (see Table 2). The extrudate was cooled in a water through, dried with blown air and cut into pellets by a suitable cutter. The TPU/CNT composite masterbatch provided by Nanocyl was diluted to TPU/4% CNT by melt blending the composite with pure TPU on the twin-screw extruder. The screw profile used for the preparation of the CPC composites is described in Table 2. For the PP/4%CNT composite production, the polymer was fed upstream by vertical gravimetric feeding; the nanotubes were added to the polymer melt by gravimetric side feeding; adequate mixing of the components were ensured by flow along various restrictive screw elements.

The operating conditions and extruder/die temperature profiles used for the PLA, TPU and PP/CNT composites are presented in Table 2, and the general extruder layout is schematically represented in Figure 1.

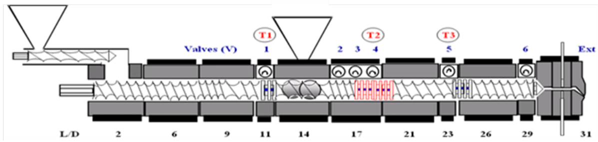

Figure 1: Extruder layout used for the preparation of the CPC composites

Processing of the CPC monofilament yarns

Monofilament yarn was processed in a prototype extrusion line, consisting of a Periplast (Portugal) single screw extruder and downstream equipment comprising die, water tank, 1st set of pulling rolls, 1st oven (for extrudate orientation), second set of pulling rolls (for drawing the filaments at the required stretching ratio), 2nd oven (for extrudate relaxation or further orientation), 3rd set of pulling rolls (for drawing or relaxation of the filaments) and winder (under controlled stress). In the experiments reported, only the first part of the extrusion line was used, i.e., no relaxation/second drawing was performed. The filament extrusion and drawing stage are schematically represented in Figure 2.

Table 2: Operating Conditions and Temperature Profiles Used for Compounding

Composite	Operating conditions	Temperature profile
PLA/4% CNT	Output = 16.5 kg/h (gravimetric feeding), screw speed = 300 rpm.	160/165/165/170/175/ 180/185/185/190/**180** (die)
TPU/4% CNT	Screw profile: 6 mixing zones with kneading blocks staggered at 90° and 45°. Cold pelletizing.	195/200/205/205/205/ 205/205/205/205/**200** (die)
PP+ 4%CNT	Output = 10 kg/h (gravimetric feeding), screw speed = 300 rpm. Screw profile: 3 mixing zones. Cold pelletizing	175/200/210/210/210/ 210/210/210/**210** (die)

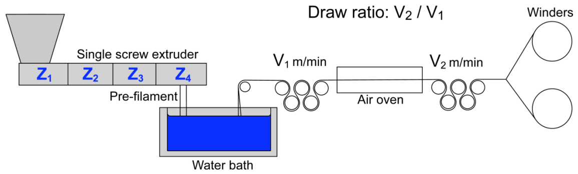

Figure 2: Equipment setup for monofilament extrusion and drawing

The set temperature profile was optimized according to the characteristics of the material to be processed. Generally, the hopper throat was cooled with circulating water and the heaters were set at temperatures increasing in the downstream direction. Setting appropriately the die temperature was mandatory. Identically, setting the temperature of the first oven was critical, as it determined the stretchability of the material. Whenever possible, the first set of rolls was adjusted to provide the same stretching ratio of the emerging extrudates, while the second set of rolls was set at increasing speeds, in order to obtain monofilaments with greater molecular orientation.

The optimized set of experimental conditions for monofilament processing is summarized in Table 3.

Table 3: Processing Conditions for the Monofilament Yarns

Composition	**Temperature profile (ºC)**	**Oven Temperature (ºC)**
PLA/4% CNT	185/185/180/175 (Die)	65 ºC
TPU/4% CNT	205/210/215/210 (Die)	50 ºC
PP(50%) + PCL/4%CNT (50%)	175/185/195/197 (Die)	154 ºC
PP/4% CNT	150/185/190/195 (Die)	162 ºC

Characterization of the CPC monofilament yarns

Tensile testing

The monofilaments produced were characterized by tensile testing on an Instron 4505 universal testing machine. The filaments were stabilized in a temperature controlled environment at 23 °C for at least 48 h before tensile testing. At least five 100 mm long monofilament samples were cut and tested using a grip distance of 50 mm. The test speed was 5 mm/min.

Electrical characterization

The volume resistivity of the samples was obtained by measuring the characteristic I–V curves at room temperature with a Keithley 6487 picoammeter/ voltage source. The voltage was varied from -10V to 10V, and the corresponding current was measured. The resistivity was calculated accounting for the geometrical factors of the filament. The filament length between contacts was approximately 65 mm. At least 3 samples were analysed for each type of composite.

Preparation of the fabrics containing CPC monofilaments

The CPC monofilaments prepared were used in the production of fabrics with different types of structures, namely satin, serge and taffeta. The fabrics were tested for surface and volume electrical resistivity, using a High Resistivity Keithey - *Keithey 8009 resistivity test fixture* - and a Low Resistivity Keithey – Keithey 2000 Multimeter.

Preparation of seamed textiles with CPC monofilaments

The CPC monofilaments were used as sewing threads to produce seamed textiles and embroideries, as an alternative for the production of textiles incorporating sensing monofilaments

RESULTS AND DISCUSSION

Composite Monofilaments

The tensile test results obtained for the PLA, TPU, PP and 50% PP / 50% (PLA/4%CNT) monofilaments produced are summarized in Table 4.
The monofilaments presented poor tensile properties at low draw ratio, increasing at higher draw ratio. Nevertheless, the tensile properties were sufficient to allow the preparation of model textile samples.
The volumetric electrical resistivity results obtained for the composite filaments are presented in Table 5. The composite filaments showed low resistivity for all compositions; TPU-CPC monofilament composites presented low resistivity, remaining almost constant for 1.2 and 2.6 drawing ratios, but increasing two orders of magnitude for the 4.0 drawing ratio.

Electro-conductive woven substrates

Using the CPC monofilaments extruded, namely PP+PPMA+4% CNT and TPU+4%NTC, different fabric structures were produced, in order to analyze the ability of the material to be woven and also, using one of the compositions, to study the influence of different structures on electrical conductivity.

Fabric Structure

In the following figures, it is possible to see the surface on both faces of a fabric, according to its structure. Figure 3 shows a serge structure. Being the colour of the warp yarn white and the colour of the weft yarn green, it is possible to see that on the left side of the figure (bottom face) the warp yarn is more visible and on the right side (top face) the weft yarn is more visible than the white yarn. This fact can lead to different results in terms of the conductivity of the textile material (as textile sensor), if a conductive yarn is used as warp or weft yarn. Another example can be seen in Figure 4, where a satin structure is presented.

Table 4: Tensile Test Results for the PLA/4% CNT and TPU/4% CNT Monofilaments.

Material	Drawing Ratio	Modulus (MPa)	Tensile Strength (MPa)	Strain at break (%)
PLA/4% CNT	1.3	1407±554	39±3	2.0±0.3
TPU/4% CNT	1.2	36±4	20±1	> machine limit
	2.6	86±8	15±2	160±97
	4.0	152±51	26±2	148±21
PP/4% CNT	1.2	1613±158	32±2	8±1
	4.0	5532±1058	177±56	7±4
	10.0	10097±205	280±79	4±1
50%PP/ 50% PCL/4%CNT	1.2	815±40	26±1	26±9
	4.0	1285±179	90±13	61±20

Table 5: Volume Electrical Resistivity Results Obtained for the Composite Monofilaments.

Monofilament Composition	Drawing Ratio	Diameter (mm)	Resistivity (ohm.m)
PLA/4% CNT	1.3	0.8	0.14 ± 0.03
TPU/4% CNT	1.2	1.0	13 ± 2
	2.6	0.6	82 ± 8
	4	0.5	5000 ± 2300
PP/ 4% CNT	1.2	0.87 ± 0.01	5.4 ± 2.4
(50%) PP + (50%) PCL/4%CNT	1,2	1	3.1 ± 1.7
	4,0	0.5	1.1 ± 0.3

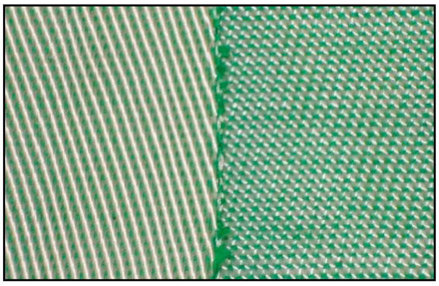

Figure 3: Bottom and top face of a serge

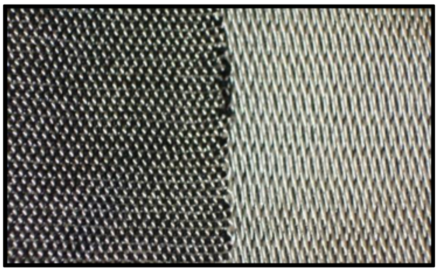

Figure 4: Bottom and top face of a satin

Other parameters should be considered to choose the appropriate fabric structure, such as the mechanical properties of the textile material.

PP + 4% CNT fabrics

Different structures were produced, considering that according to the structure chosen, the electrical conductivity behaviour will be different, as the filament will be arranged on the surface of the fabric in a different position.

Table 6 presents the list of woven fabrics that were produced with PP / 4% CNT monofilament (draw ratio of 7.65, 61 tex) on the weft and PES HT (110 tex) on the warp. Six samples were produced, using plain, inverted serge and false satin structures, in order to measure surface and volumetric resistivity.

Table 6: Fabrics Produced with PP / 4% CNT Monofilaments.

Fabric	Structure	Pass/cm	Yarns/cm	Whidt
1	Taffeta	8	25	5,4
2	Taffeta	8	25	8,1
3	Inverted serge	13	19	10,0
4	Taffeta	24	61	1,0
5	False satin of 4	14	24	8,5
6	False satin of 4	6	24	10,1

Electrical characterization

The resistivity of the different fabric structures were measured using the Keithley Resistivity Fixture.
The results obtained are shown in Figures 5 and 6.

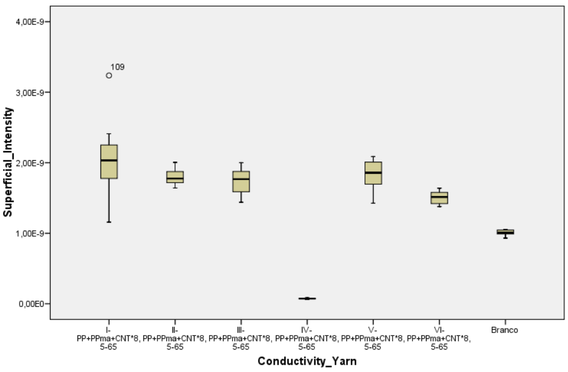

Figure 5: Surface resistivity.

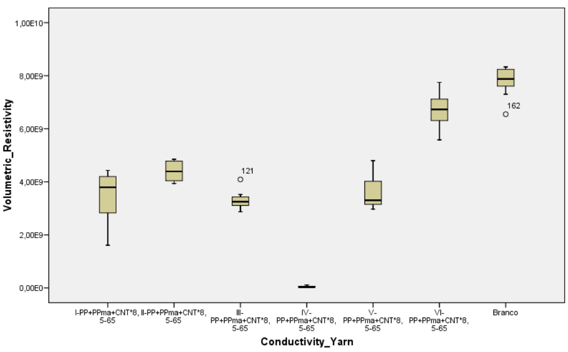

Figure 6: Volume resistivity.

Different electrical behaviour was detected on different fabric structures, as illustrated in the Figures. This type of experiments will be carried out in the future with different polymers.

Smart and multifunctional seamed textiles

The use of CPC filaments as sewing threads (conductive yarn), to produce sensitive garments was studied.

Sewing process

Experiments were performed using different conductive and non-conductive yarns already available in the market, as sewing threads, in order to analyze the effect of these materials on some parameters that characterize the sewing process and also the effect of the sewing operation on the conductivity of the threads. CPC monofilaments produced by extrusion were also tested as sewing threads.

A lockstitch sewing machine (stitch point 301) was used to perform the seams. This stitch point was selected because it is also used on embroidery sewing machines. Stitch point 301 is formed with two threads: the needle thread and the bobbin thread. The experiments were made using the different threads both as needle or bobbin thread. Different parameters are fundamental for a proper seam: thread tension, stitch balance, presser foot pressure and stitches per point. Also, the type of seam and sewing thread are relevant.
The results obtained did not show a distinctive behaviour from ordinary sewing threads.

In terms of tensions generated during stitch cycle, it is clear that needle threads with great thickness will generate greater tensions during the stitch cycle. If conductive threads are used as bobbin threads no significant difference is noticed on the tension generated on the needle thread. Bobbin thread is also under lower mechanical demands from the seam formation process and consequently less damage will be produced on the sewing thread. These facts suggest that conductive threads could be used as bobbin thread.

Use of conductive filaments on seams or embroidery

As referred before, the monofilaments could be used in sewing machines, namely on lockstitch sewing machines (stitch point 301). Seams made using PP+4% NTC are presented in Figure 7.

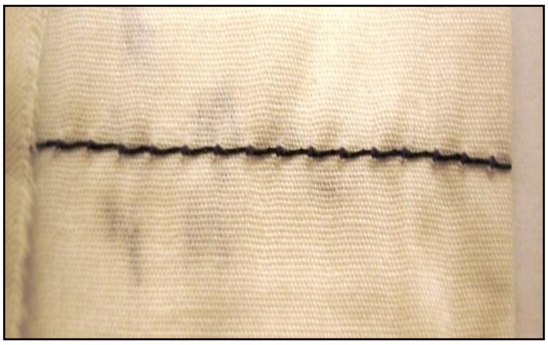

Figure 7: Seam made with PP/4%CNT monofilament

Conductive monofilaments can be attached in garment also as presented in Figure 8. In this way, current sewing threads are used and the monofilament is not subjected to the action of the sewing elements.
Another form of introducing conductive yarns into garment may be by embroidery. An example is presented in Figure 9, using PP/4% CNT.

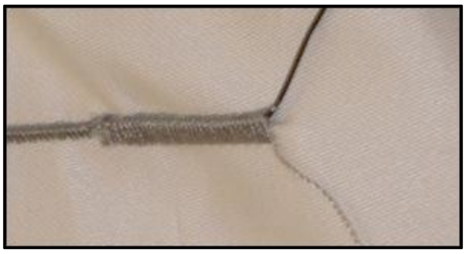

Figure 8: Attachment of TPU/ 4% CNT monofilament

Figure 9: Embroidery with PP / 4% CNT

Using this technology, it will be possible to produce surfaces on the garment that are conductive, being an advantageous method to improve the interface between the conductive textile material and the external environment.

Development of a multifunctional textile prototype

Several filaments were tested in the sewing machines, namely polymer/CNT monofilaments obtained with PCL and PLA (for liquid sensing) and PP(50%) + (PCL/4%CNT)(50%) (for temperature sensing), and a prototype was produced.
Due to the monofilament characteristics, namely its cross-section and stiffness, it is very difficult to use it as sewing thread, particularly as needle thread. However, it is possible to use it as bobbin thread on a lockstitch sewing machine. In this way, the conductive filament can be applied in a very flexible way on a piece of garment or fabric, forming a surface rich in conductive filament, as represented in Figure 10.

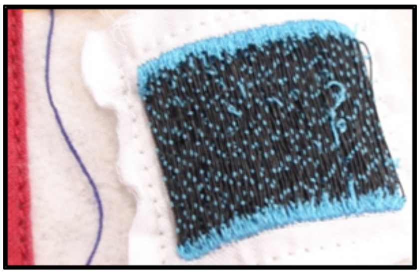

Figure 10: Fabric surface obtained using the monofilament as bobbin thread on a lockstitch sewing machine

Based on sewing technology, PP/(PCL/4%CNT) multifilaments were used to produce textile sensors. The sensors, after being annealed, were assembled in the garment. The prototype garment produced is shown in Figure 11.

Figure 11: Prototype garment produced with sensing monofilaments incorporated

CONCLUSIONS

Monofilament composites formed with different polymers and carbon nanotubes were produced. The monofilaments presented electrical conductivity and sensor activity, depending on the matrix polymer.
The monofilaments were used in the production of fabrics with different structures, and as sewing threads

to produce seams and embroideries. The products obtained presented electrical conductivity.
A prototype garment was produced incorporating the carbon-polymer monofilaments.

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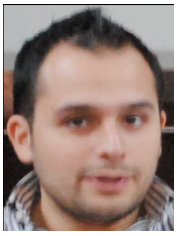

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