INFLUENCE OF INCORPORATED NANODIAMOND PARTICLES ON MECHANICAL PROPERTIES OF COMPOSITE MATERIAL BASED ON MULTI-LAYER PVA NANOFIBER TEXTILES

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Abstract

Nanofiber textiles can be efficiently modified using nanoparticles to accomplish desired properties. Such modification, often achieved by using silver, copper ions or even nanodiamonds (NDP), can render the nanofiber textiles with their antibacterial character. From practical point of view any uses of nanofibers must also pursue enough high mechanical strength and/or stability. The present study investigates the influence of NDP on mechanical properties of multi-layer PVA nanofiber textiles. The particles of a diameter equal to 5 nm were incorporated into double- and triple-layer textiles, while the single-layer samples were prepared as the reference. The diameter of PVA nanofibers varied from 100 to 300 nm. We characterized the tensile strength, stiffness and ductility of fabricated nanofibers by using a conventional method – a tensile test. We found that the NDP-enriched nanofibers reveal antibacterial character. However, none or negligible influence of NDP additions on the tested mechanical properties was observed.

Key worlds:

Nanofibers, PVA, nanodiamonds, electrospinning, mechanical properties, SEM.

1. INTRODUCTION

The properties of nanofiber textiles towards preferred performance can be efficiently modified using incorporated nanoparticles. If the nanofibers are prepared using needleless electrospinning, the nanoparticles of various types and shapes can be simply directly added into the polymer solution in a desired concentration. Such approach partially ensures a homogeneous distribution of the particles.

Nanodiamond particles (NDP) are currently investigated in many research fields as material engineering, pharmacy, drug delivery, imaging or even antibacterial uses. Stiffness, thermal conductivity and biocompatibility of NDP allow a large number of their applications when incorporated in nanofibers. NDP are widely produced by the method of detonation synthesis, which is relatively cheap. However, for NDP incorporation into nanofibers it is necessary to ensure their even distribution within the matrix in order to tailor their properties.

Maitra et al. [1] primarily focused on the mechanical properties of thin PVA-NDP layers / membranes cast in Petri dishes. The thickness of each layer was equal to 500 nm and the diameter of NDP reached about 5 nm. Transmission electron microscopy (TEM) and the method of small angle X-ray scattering (SAXS) demonstrated that the concentration of NDP in range up to 0.6 wt. % provides their homogeneous distribution within the PVA matrix. The most concentrated PVA-NDP samples showed an increase in the crystallinity by 34 %, stiffness by 98 % and tensile strength by 79 %, compared to plain PVA reference samples. The incorporation of higher NDP concentrations NDP (2.0 wt. %) in nanofiber textiles was explored by Wang et al. [2]. In their study, the dispersed NDP (with diameter 3-10 nm) increased the stiffness by 155 % and tensile strength by 89 %. However they observed agglomeration of NDP due to employing high concentration. The advantage of incorporating NDP compared to carbon tubes is discussed in the paper by Morimune et al. [3]. The NDP (1.0 w. %) showed more significant increase in the composite stiffness and thermal conductivity. The study performed by Parizek et al. [4] explored the effect of poly(lactic-co-glycolic) acid (PLGA) processed by electrospinning enriched by bioactive NDP on human-like osteoblasts. A drawback of NDP use can be attributed to the weight increase and therefore it is required for many applications to enrich the textiles by a few units of weight percentage of NDP [5, 6].

The main goal of this study was to successfully prepare and test the mechanical properties of composite material based on multi-layer PVA nanofiber textiles with one layer containing NDP. The double-layer PVA composite had been already tested in a previous study [7], demonstrating a composite behavior with a perfect bond between the layers based on results of mechanical testing in tension. The tested samples PVA samples had been also thermally stabilized, which is necessary to provide the perfect bond and sufficient integrity of all nanofiber textiles made of polymers on the water solution basis [8, 9].

2. TESTED SAMPLES

The nanofiber textiles for our study were produced from a PVA water solution using the needleless electrospinning method. Nanospider NS Lab 500S (Elmarco, Czech Republic) device was used for manufacturing the tested nanofiber textiles. This device is located in the laboratories of the Czech Technical University in Prague, Faculty of Civil Engineering. The production line settings were as follows: voltage set to 81.3 kV and the distance between electrodes 140 mm, the cylindrical electrode (600 mm in length) rotating with at frequency of 5 Hz and the nanofiber textiles were deposited on a supportive PP geotextile substrate with an area density of 18 $g.m^{-2}$ and antistatic treatment. The preparation process was accomplished in standard laboratory conditions at the temperature of 25 °C and relative humidity of about 42 %. The polymer solution consisted of 375 g PVA solution (16 % water solution, Sloviol R, produced by Fichema Ltd., Czech Republic), 117 g distilled water, 4.4 g glyoxal and 3 g phosphoric acid (75 %). The last two compounds were used as cross-linking agents; the stabilization of the produced PVA fibers was accomplished by exposure to an elevated temperature of 140 °C for 10 minutes. NDPs (NanoAmando, New Metals and Chemicals Corp. Ltd. (Kyobashi, Japan)) with diameter (median D50) of 5 nm were added into the disposed PVA polymer and homogenized using a stirrer and an ultrasonic bath [10]. A concentration of NDP within the PVA polymer solution was 1 % of the PVA mass. The NDP were incorporated into the PVA solution and added by means of electrospinning as the last layer of double- and triple-layer textiles, while the single-layer samples were prepared as the reference. The first layer was the same for all tested nanofiber textiles. Specification of the tested nanofiber textiles is summarized in Tab. 1. The produced nanofiber textiles had a various area density ranging from 3.2 to 6.6 $g.m^{-2}$, see Tab. 2.

Tab. 1: Basic characterization of tested PVA multi-layer nanofiber textiles

Samples	Number of layers	Composition of nanofiber textiles	Electric Current (mA)
A	one	PVA	0.21
B	two	PVA+	0.21
		PVA with NDP (1% wt.)	0.19
C	three	PVA+	0.21
		PVA+	0.19
		PVA with NDP (1% wt.)	0.19

The diameter of the produced PVA nanofibers ranged between 100 and 300 nm, see Fig. 1. The NDP additions do not change the character of textiles, i.e. size and arrangement of individual fibers, as demonstrated by the SEM images provided in Fig. 1. The images also clearly show the connection of individual fibers at their intersection as a consequence of the crosslinking process, creating a compact spatial structure.

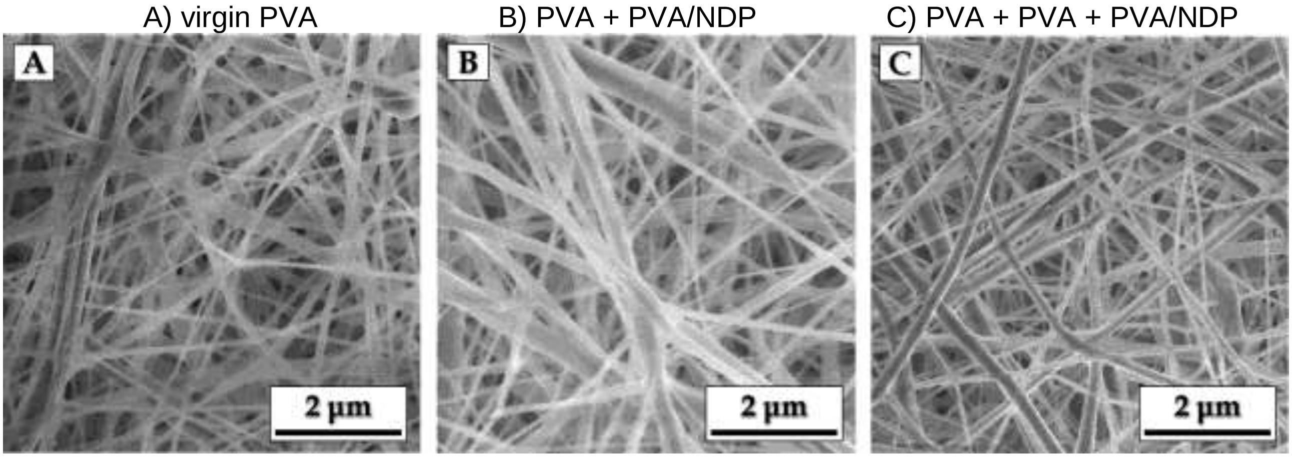

Fig. 1: SEM images of the tested nanofiber textiles (from left to right): samples A, samples B and samples C. All samples were thermally stabilized, scale bar is 2 μm.

In order to obtain statistically representative data at least 6 specimens were tested for each material type and the weight per area was measured for each sample individually. The 2 cm × 12 cm specimens were cut off from the nanofiber textiles and the ends of each specimen were reinforced by an adhesive paper tape to withstand the attachment of the textiles into the clamps of the testing machine. The clear length of the tested specimens was equal to 10 cm, which was sufficiently large to provide a representative data with respect to the size of individual fibers [10, 11].

3. EXPERIMENTAL METHODS AND RESULTS

The experimental testing of stiffness, tensile strength and elongation was carried out on using the LabTest 4.100SP1 device. The measuring range was set to 50 N maximum where the accuracy exceeds 0.1 % (at the magnitude of 2 N). The value of Young’s modulus (elastic stiffness) was determined during a standard tensile test as a tangent of the linear part of the experimentally obtained stress-strain diagram, where the stress is normalized to the weight per area and the width of the individual tested nanofiber textiles. Fig. 2 shows a comparison of Young’s moduli for all tested nanofiber textiles.

From the obtained results it may be observed that the presence of NDP has a negligible impact (if any) on the elastic response of the nanofiber textiles to tensile stresses. The highest standard deviation in stiffness was detected in the case of the reference textiles (sample A), equal to approximately 20 %. It can be assumed that the bond between individual layers was perfect in the case of multi-layer composites (the samples B and C). The values of tensile strength (Tab. 2) were determined as the maximum value of stress reached during the experiment. The elongation parameter was determined as a ratio of the absolute maximum elongation reached during the testing and the original length of the unloaded specimen.

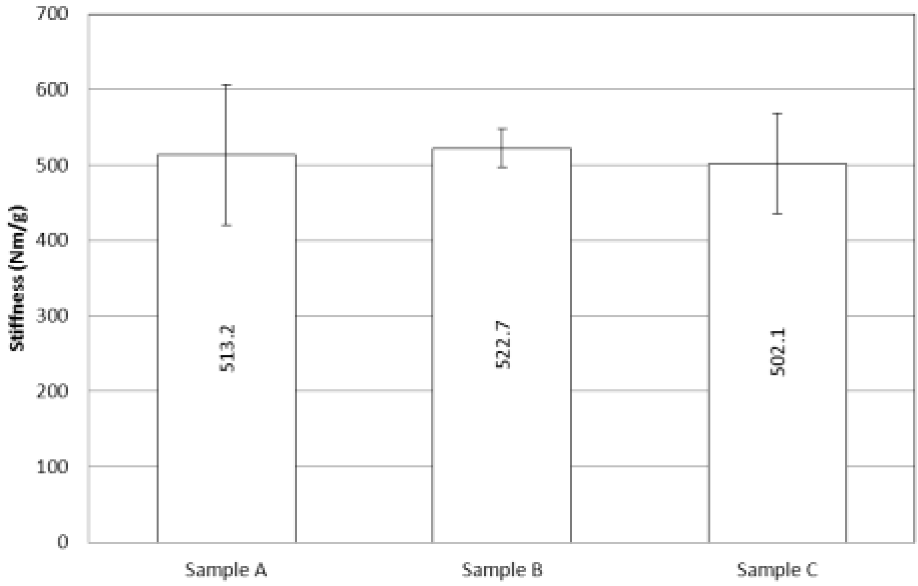

Fig. 2: Comparison of stiffness parameters for the tested nanofiber textiles.

Tab. 2: Basic characterization and mechanical properties of the tested PVA multi-layer nanofiber textiles with standard deviation of the measurements

Sample	Weight per area ($g.m^{-2}$)	Tensile strength (Nm/g)	Elongation (%)
A	3.2 ± 0.2	204 ± 25	8 ± 1
B	4.1 ± 0.2	200 ± 16	7 ± 1
C	6.6 ± 0.4	224 ± 31	8 ± 1

The obtained measurement data indicate that NDP did not increase the mechanical resistance of the nanofiber textiles with respect to tensile stresses as suggested by Wang et al. [2]. However, the type of NDP in their study was different from NDP used in our case (a diameter, mean size distribution, chemical composition of NDP surfaces). As well as they tested a single layer system and used a different configuration of their experimental setup for testing. Presented results correspond with the ones which were presented on multilayer nanofiber textiles previously [7]. The mechanical properties of nanofiber textiles are not depend on number of layer in multilayer systems.

4. CONCLUSIONS

The multi-layer PVA nanofiber textiles with one layer containing NDP can be considered for a practical application because of their relatively low cost resulting from the efficient arrangement of the particles within the single layer only. So treated layer can be exposed to more aggressive environment and to provide the treatment for surfaces of materials. According to our study the presence of NDP did not degrade the mechanical properties (stiffness and tensile strength) of nanofiber textiles. Therefore PVA/NDP composites are not limited for further applications. Thus, the NDP-enriched PVA textiles can find use as an antibacterial treatment of surfaces [12], as well as in regenerative medicine due to their compatibility with the human tissues [4, 13]. The large-scale application in civil engineering [14] is also one of the many options for the use of nanofiber textiles with NDP.

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